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USAAVLABS TECHNICAL REPORT 66-28

INVESTIGATION OF PERFORMANCE OF MULTIPLE GAS GENERATORS WITH A COMMON EXHAUST

By

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May 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-274(T)

GENERAL ELECTRIC COMPANY
WEST LYNN, MASSACHUSETTS

U. S. ARMY MATERIEL COMMAND

DEPARTMENT OF THE ARMY
U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report has been reviewed by the U. S. Army Aviation Materiel Laboratories and is considered to be technically sound. The work was performed under Contract DA 44-177-AMC-274(T) as an exploratory program in order to investigate the effect on performance and feasibility of multiple gas generators with a common exhaust.

Task 1M121401A14415
Contract DA 44-177-AMC-274 (T)
USAAVLABS Technical Report 66-28
May 1966

INVESTIGATION OF PERFORMANCE OF MULTIPLE GAS GENERATORS WITH A COMMON EXHAUST

Final Report
GE Report No. TM65SE-20

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ABSTRACT

A system wherein multiple engines exhaust into a common exhaust is analyzed on both a steady-state performance and transient response basis. A failure analysis of the system is also included.

Engine to engine variations have been considered together with the effects of externally induced mismatches.

It is concluded that maximum power is obtained by rating the engines on a T5 basis and trimming the exhaust area upon installation.

It is shown that the greater the number of engines combined in a common exhaust, the lower the average performance compared to separately ducted engines; however, the averaging effect of the number of engines and the trim method recommended keeps the minimum system performance above that which would be calculated from single-engine guarantee performance.

A fundamental problem in the common engine system is that of acceleration delay or hangup resulting in deceleration during transient conditions. This problem can be eliminated in the two-engine system by using a high idle speed and can be prevented in the four-engine system by a combination of high idle speed and a simple gas generator coordination control.

If accessory power is to be extracted, this must be extracted equally from all engines.

Although the characteristics of the T64 engine and the hot gas cycle rotor were used, the results are believed to be applicable to a wide range of engine and aircraft configurations, including the lift fan and cruise fan. However, the simplicity of control of the two-engine system probably makes this system more attractive than the four-engine system.

ACKNOWLEDGMENT

Data and performance curves for the hot gas rotor for use in this study were supplied by the Hughes Tool Company (Aircraft Division).

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SYMBOLS

A	Ratio of actual rotor tip nozzle area to the design value of rotor tip nozzle area
A_8	Total physical flow area of rotor tip jets
B_N	A signal from the diverter of the nth engine to the transient speed coordinator. It is used to remove an engine from the transient coordination system in the event that it is diverted
C_y^x	Partial derivative of x with respect to y
C_N	A signal from the diverter of the nth engine to the transient speed coordinator. It is used to remove an engine from the transient coordination system in the event that it is diverted
Dn	A diverter function for the nth engine Dn = 1 if the engine exhaust is diverted Dn = 0 if the engine exhaust is not diverted
Dr	The droop rate of the Ng governor
EPR	Engine pressure ratio, PT7/PT2
F_{1-18}	Functions used in the DYNASAR Program, see section entitled "Transient Performance" for definition.
F_A, F_B, F_C	Functions extracted from a computed diverter valve performance map.
F_N	The function of the transient speed coordinator
HP	Horsepower
H_7	Enthalpy, total at station 7
H_{s9}	Enthalpy, static, after isentropic expansion from station 7 to ambient pressure
I_G	Polar moment of inertia of the gas generator rotor = 12.67 (Lb-Ft sec/% Ng)
K_{1-10}	Constants used in the DYNASAR Program
LS	Load signal from collective pitch to the fuel control in Wf/PS3 units
Min Ratio	Minimum Wf/PS3 ratio (a control function)

% Ng	Percent gas generator speed
% Ng_0	Initial gas generator speed (%)
% Nr	Percent rotor speed
% Nr set	Desired percent rotor speed
PT2	Compressor inlet total pressure (psia)
PS3	Compressor discharge static pressure (psia)
PT5	Turbine discharge total pressure (psia)
PS6	Static pressure at point where engine flows mix (psia)
PS'6	Static pressure just upstream of the diverter (psia)
PT6	Total pressure at point where engine flows mix (psia)
PT7	Flow weighted average total pressure at mixing plane
R_y^x	Partial derivative of x with respect to y — used for Ng and P5 derivatives
S	Complex operator resulting from Laplace transformation $\left(\frac{1}{sec}\right)$
T2	Compressor inlet total temperature (°R)
T4	True total temperature of gas entering turbine (°R)
T4M	Measured value of T4 (°R)
T5	True total temperature at gas generator exhaust (°R)
T5M	Measured value of T5 (°R)
TS6	Static temperature at point where engine flows mix (°R)
T6	Total temperature at point where engine flows mix (°R)
T_V	Volumetric time constant of aircraft ducting (sec)
η c	Gas generator compressor adiabatic efficiency
η t	Gas generator turbine adiabatic efficiency
μ	Mean value of subscripted parameter
σ	Standard deviation of subscripted parameter

ρ True correlation coefficient

$\hat{\rho}$ Estimated correlation coefficient

τ Torque

τA Torque available to drive the rotor (Lb-Ft)

τR Torque required to drive the rotor (Lb-Ft)

τG Gas generator unbalanced torque (Lb-Ft)

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SUMMARY

The analysis of a multi-engined common exhaust system was performed in compliance with Contract DA 44-177-AMC-274(T).

The object of the program was to analyze multiple engines exhausting into a common exhaust on both a steady-state performance and transient response basis with both engine-to-engine variations and externally induced mismatches.

To accomplish this, two extensive computer programs were constructed, one for transients and one for steady-state performance. Although the characteristics of the T64 engine and hot cycle rotor were used, the results are believed to be applicable to a wide range of engine and aircraft configurations.

To analyze throttle and load bursts and chops and engine failures, the DYNASAR digital transient program was used. This simulated four engines and their controls, the common ducting and rotor system, engine coordination controls when required, rotor speed control, and diverter valve and tip nozzle systems.

This program was used to evaluate the effect of the many different variables which influence transient response. From this analysis it was concluded that in order to prevent engine hang-up and roll-back in a two-engine system, an idle speed higher than normally used is required. In the four-engine system an engine speed coordination scheme, in addition to a high idle speed, is required to prevent hang-up on attempted rapid accelerations. A relatively simple speed coordination scheme for the four-engine system is proposed.

In order to ascertain the performance level of common exhaust systems including effects of engine-to-engine variation and deterioration of engines, a digital computer program using a random analysis technique was set up which is capable of analyzing from one to six engines combined with a common exhaust with several trimming schemes automatically. This program was used to obtain the steady-state performance under various rating and trim methods. It was concluded that the maximum performance is obtained by rating engines individually on exhaust temperature (T5), and, on installation in the aircraft, trimming the tip nozzle area (A8) to compensate for interreaction effects and to minimize the effects of deterioration. With this rating and trimming scheme, performance of common exhaust systems is very satisfactory.

The failure analysis demonstrated that the diverter valves and tip nozzles must be prime reliable and that initiation and sequence of operation must be automatic, to eliminate flow reversal in the failed engine.

CONCLUSIONS

RATING AND TRIMMING METHOD

Of the three rating and trimming methods analyzed, maximum power was obtained by the following method: (a) rating the engines on a T5 basis with an exhaust area which represents the average effective area they will see in the installation, (b) setting engine control topping speed to rated T5 on preshipment checkout with a fixed nozzle representing this area, and (c) trimming A8 open on initial installation of engines in the aircraft to bring T5 on the poorest engine (it will run over-temperature due to the higher back pressure from the better engines) down to rated T5 with the engines at their pre-set topping speed.

MAXIMUM PERFORMANCE AVAILABLE

The more the number of engines combined in a common exhaust, the lower the average performance compared to separately ducted engines. A two-engine system has approximately 1.2 percent less average power and a four-engine system has approximately 2 percent less average power including the benefit from A8 trimming.

However, the averaging effect on multiple-engine aircraft and the averaging effect of the trim method, above, keep minimum aircraft propulsion system performance approximately 1 percent above single-engine guarantee performance.

In a common exhaust system comprising four average engines, if one engine deteriorates the effect on overall system power is approximately the same as if all engines had deteriorated the same amount. However, in a random group of engines, deterioration of an engine will not affect the power of the system until the performance of that engine falls below the minimum engine in the group.

Thus the power of the system is determined by the performance of the minimum engine.

ACCELERATION HANG-UP

Engine hang-up (acceleration delay) and roll-back (deceleration due to high back pressure) are fundamental problems in a four or more engine common exhaust system. The primary cause is initial idle speed mismatch. One engine, in any random group of four engines, would be expected to hang-up on attempted rapid acceleration from the idle speed normally used on the T64 engine ($\sim$3 percent of maximum power). By use of slow rates of rotor loading (3.0 seconds from 0 to maximum), acceleration can be accomplished without hang-up.

By using a gas generator idle speed which produces approximately 10 percent of maximum power, no hang-ups would be expected in a two-engine system from the speed mismatch of up to 7 percent even when fast rates of rotor loading are used (1.0 second from 0 to maximum). The gas generator idle speed corresponding to this power is about 87 percent.

By use of this high idle speed and a simple gas generator coordination control, hang-ups can be eliminated completely in the four-engine system.

The use of a variable tip nozzle area, A8 , improves the tolerance to mismatch, but the duration of the accelerations is approximately twice that for the Ng coordinator. Also, the system would be mechanically complicated and would still have the psychological problem of mismatched speeds during acceleration.

STEADY-STATE TEMPERATURE CONTROL

There is no requirement for a steady-state T5 control.

ROTOR SPEED CONTROL

Although a hot cycle rotor system is inherently more stable than a geared rotor system, load compensation of the form normally used on a geared rotor system is required in order to obtain a steady-state error of less than 5 percent Nr while maintaining stability.

POWER EXTRACTION

If accessory power can not be taken from the rotor, the best method would be balanced loading of engine accessory pads. Unequal accessory loading or customer bleed between engines must be avoided because of the resulting acceleration mismatch and the high performance penalty incurred (four times the power loss for matched extraction).

FAILURE ANALYSIS

Following an engine failure, the failed engine decelerates very rapidly and may cause flow reversal in the failed engine. Failure of the tip nozzles closed or open causes a large increase in temperature or a large reduction in power, respectively.

OPERATION WITH A CRUISE FAN

Since cruise fans can be designed to have partial arc admission and do not normally require speed control, their operation should not be affected by use in conjunction with a common exhaust system.

STARTING AND SHUTDOWN

Starting and shutdown would of course be in the diverted mode. It is necessary for the pilot to match speeds only within a 10 percent band before switching from diverted to common exhaust operation. In the two-engine installation with the high idle speed, the second engine can be switched over to common exhaust at any speed above idle.

APPLICABILITY TO T65 GROWTH ENGINES

The T64 S4A and S5 growth engines are expected to have a larger gas generator speed range from 10 percent power to full power. This will increase acceleration hang-up potential. However, they also will have increased acceleration margin due to lower compressor operating line. The net result is that the conclusions arrived at with the present T64 will be applicable to growth versions.

RECOMMENDATIONS

TWO ENGINE SYSTEM

In the two-engine system, it is recommended that the features outlined below be utilized.

Rating

The engines should be rated individually on a T5 basis and the nozzle area of the propulsive device trimmed, rather than engine speed, to obtain maximum power on initial installation. Provision should be made for adjusting A8 from -2 to +5 percent in effective area.

For some operations, where guarantee power is adequate, it is recommended that the EPR rating method be considered since it eliminates the need for A8 trimming and guaranteed power is constant during engine life. However, average initial performance would be 3 percent lower.

Hang-Up

A high idle speed with no coordinating control should be used to prevent hang-up or roll-back. With the T64 engine the high idle speed is 87 percent Ng on a standard day. At other T2's the same speed differential from maximum should be maintained. This function can be achieved by profiling the engine fuel control cam accordingly.

Rotor Speed Control

Collective pitch feedback to engine control should be provided.

Power Extractions

If it is not possible to extract power from the rotor, it is recommended that balanced power be taken from the accessory gearboxes. If gas power is bled from the common exhaust, it must be continuous or a very small quantity if intermittent. If compressor discharge bleed is used, it must be drawn equally from the engines.

Failure Analysis

In order to avoid blow-back following an engine failure, it is necessary to make the initiation of diverter valve operation automatic. This can best be done by use of differential engine speed signal.

In order to remove the possibility of large overtemperatures or large losses of power, the diverter valve and tip nozzle systems should be designed for maximum possible reliability.

FOUR-ENGINE SYSTEM

All of the recommendations for the two-engine system, above, apply with the following addition:

An Ng coordinating control should be incorporated to avoid acceleration hang-up. This coordinating control should be in the form of a speed comparing amplifier acting on the fuel control to reduce fuel flow to any engine which leads the slowest engine by more than 3 percent. A system specification for such a speed coordinating control scheme is included herein.

INTRODUCTION

Gas generators exhausting into a common plenum do not operate independently because of the cross communication of exhaust pressure between engines and the requirement that the exhaust gas from individual engines must exit through a common area. The transient characteristics and steady-state minimum power capability of the system will be affected, in general, adversely.

The basic steady-state problem in the common exhaust system is one of achieving the maximum power from the system while ensuring that all the engines are within the limits of speed and temperature. At part power there is no steady state matching problem, since all engines will be at reduced temperature and speed.

As an example, consider four perfectly matched engines operating at the same speed and at maximum temperature. Assume that in one case they are in a common duct and that in another they are separately ducted. Assume also that there is a deterioration of components in one, such that this engine increases temperature.

In the separately ducted system, the pilot reduces the temperature on the poor engine by reducing the speed on that engine. The system power loss is, therefore, equal to the power loss on the one engine.

In the common exhaust system, the poor engine also goes overtemperature and the exhaust pressure must be reduced. Reducing speed on the poor engine will be shown to be insufficient; consequently, the speed of the three good engines has to be reduced until the temperature of the poor engine is brought within limits. The system power loss is the sum of the deterioration loss and the loss due to reducing the speed of the good engines and is, therefore, approximately four times as great as the separately ducted system. By use of a suitable trim method, this power loss can be reduced.

A digital computer program was developed which, by means of the Monte-Carlo Analysis technique, established the performance of the system in terms of average powers and power spread. This program is utilized in the selection of the rating and trim methods to be used in common exhaust systems.

In order to obtain the transient performance of the system, a digital computer program was established. This program, the Dynamic System Analyzer (DYNASAR), utilizes analog computer techniques to simulate the system.

One of the primary difficulties with the common exhaust system is the interdependency of engines during acceleration. As explained above, the exhaust conditions from one engine affect the performance of the other engines in the system. As an example of this effect during acceleration, consider a four-engine system with one of the engines at a lower idle speed than the others. This low engine is running at a higher operating line than the others since it is sensing a higher back pressure. As the ganged throttles are increased, all engines move on to the acceleration schedule.

The fast engines sense a slightly lower back pressure and hence accelerate at an increasingly faster rate compared with the slow engine. When the speed differential between the fast and slow engines is sufficiently large, the slow engine ceases to accelerate and in fact may roll back.

This results in the system's running at a much reduced power, and obviously this can not be tolerated.

The initial transient performance runs were, therefore, made with the aim of developing a method by which the system could accelerate from a reasonable mismatch without hang-up or roll-back.

In order to obtain a complete simulation of an aircraft system, a hot gas rotor system was incorporated into the DYNASAR program. The system used was similar to that used in the Hughes Tool Company XV-9A Hot Cycle Research Aircraft at present flying with a two-engine common exhaust system.

The effect of the rotor system upon the performance was obtained together with the rotor stability and governing requirements.

Typical diverter valve dynamics were built into the system, and the effect of the operation of these after engine failure was obtained. A failure analysis of the complete system was conducted.

STEADY-STATE PERFORMANCE

INTRODUCTION

A multiple gas generator common exhaust system, such as the hot gas cycle rotor, responds differently to engine performance differences than does a separately ducted engine installation. This section illustrates the reactions to performance differences and explains a feasible rating system and operating procedures to obtain maximum performance.

Two unique characteristics of the common exhaust system have an effect upon the system's performance. These are: (a) the requirement for static pressure balance at the mixing plane and (b) the sharing of mismatched exhaust conditions, e.g., T5, W5, by the other engines in the systems.

These two characteristics are unique to the common exhaust and not to the power utilizing device, which may be any of the following: jet nozzle, hot cycle rotor, cruise fan, lift fan, power turbine, etc. It is possible to alter the interrelationship of engines in a common exhaust by the use of an independently variable exhaust geometry or variable cross bleed. These systems detract from the simplicity and weight saving of the common exhaust to the point that they were not further considered.

In addition to the above characteristics, there are the two fundamental considerations of flow continuity and turbine energy balance, which must be regarded as the framework for understanding the common exhaust system response.

Continuity applies both to the individual gas generators, to the common ducting and to the exhaust nozzle, whereas energy considerations relate only to the individual gas generators.

Gas generator continuity is readily visualized by considering an increase in temperature at constant speed and constant turbine inlet flow function $\frac{W\sqrt{T}}{P}$. The resulting increase in pressure to maintain continuity is approximately proportional to the square root of the temperature

Gas generator energy depends upon flow, temperature, pressure, and efficiency, and if the match of a number of common exhaust engines is disturbed, causing the available power to be reduced, some action must be taken to rectify the mismatch.

The effects of the corrective actions differ and must be considered together with nozzle continuity and exhaust pressure equality. The following description of the effects of mismatch and the subsequent action should give a good understanding of the problem.

Given: Four average engines running at maximum T5 on topping at equal speed, with isochronous governing.

Consider that upon installation in a common exhaust system one engine is poor and, therefore, reaches maximum temperature at lower than average exhaust pressure.

The temperature of this engine will increase such that its pressures match those of the good engines.

The combination of the restored pressure and increased temperature satisfies the gas generator energy and continuity requirement of the poor engine, but it means that continuity is not satisfied in the exhaust nozzle since the high temperature of the poor engine increases the average temperature in the exhaust. The exhaust pressure must, therefore, rise above its original level to offset the rise in average temperature, and this rise causes all the engines to go slightly overtemperature.

Thus the system stabilizes with the pressure slightly increased and with the temperature substantially increased on the poor engine and slightly increased on the good engines.

It should be pointed out, at this point, that the increase in temperature on the poor engine is less in the common exhaust system than would have occurred in a separately ducted system at the same airflow, due to the sharing action in the common exhaust duct. For example, one point in turbine efficiency on one engine causes a 32° increase in temperature in the four-engine common exhaust system and a 40° increase for one separated engine.

Corrective action can now be taken, and two alternatives are available: (a) the speed can be reduced on all, several, or one of the engines or (b) the speed can be maintained and the nozzle area increased. The effects of these methods are considered separately.

(a) Reduce speed on all engines until the temperature is within limits. This reduces the exhaust pressure and hence exhaust temperature on all engines equally, and the temperature differential between the good engines and the poor will be about the same. Topping is then set down to correspond to the new gas generator speed such that the poor engine is at the maximum allowable temperature and the good engines are at a lower temperature.

Reduce speed on the good engines only. This has the same effect as the previous method by reducing the mass flow. This results in a reduction of pressure in order to maintain nozzle continuity.

Reduce speed on poor engine. The reduction in speed must be far greater than in the previous case in order to reduce the mass flow sufficiently to effect the reduction in exhaust pressure. This reduction in speed, however, further increases the pressure mismatch at the mixing plane. For large decreases in performance or for systems with more than four engines, no solution is reached.

(b) Open exhaust nozzle area. As explained above, the increased temperture from one engine causes an increase in $\frac{W\sqrt{T}}{P}$ which, for a fixed nozzle area, must be reduced by a further increase in pressure. By opening the exhaust nozzle area, the increased flow can be tolerated; by further increase of the nozzle area, the pressure and, hence, temperatures are reduced to maintain continuity. In this manner, the temperature is brought within limits.

It should be noted that since there has been no reduction in speed, the mass flow has remained the same and, hence, the power reduction with A8 trim is less than in the case of reducing speed.

ANALYSIS (Performance Maps)

An analytical method was developed for estimating the performance of a multi-engine system having one or all engines with a 1.5 percent reduction in turbine efficiency.

This method uses performance maps derived from the Average T64 Engine Deck and shown in Figures 1 through 6 as functions of the nozzle relative flow coefficient. The manner in which the curves are used is described below:

Given: Three identical average T64 gas generators (Figures 1 through 3) and one low performance T64 gas generator (Figures 4 through 6) (ηt nominal) $\times$ (.985), rotor speed 100 percent, rating method T5M, A8 trim.

All four engines are to be run at the same speed; and since T5M on the poor engine is to be maximum, the static pressure at the mixing plane PS5 can be read from Figure 5. This map also gives the value of T4 and nozzle relative flow coefficient, which gives the total pressure in the exhaust and also the nozzle flow coefficient.

It is now necessary to match the remaining engines to the performance of the poor engine. Two conditions, static pressure PS5 and speed Ng, are known for three engines, and from these conditions the flow function $W\sqrt{T}$ and total pressure can be found from Figures 2 and 3.

Up to this point, the procedure is independent of the power utilizing means. The following procedure is applicable to any hot gas rotor system; specifically, however, curves supplied by the Hughes Tool Company are used to obtain the system performance.

The flow and total pressure are now averaged at the mixing plane. From Figure 7 the flow function for the nominal tip area is obtained, and when this is compared with the flow function above, the effective area ratio at the tip can be obtained from Figure 9. The available rotor horsepower for the nominal flow function is read from Figure 8, and this is combined with the power ratio from Figure 9.

A summary of the results for the various trim methods is given in Table I. This table shows the effect of the 1.5 percent deterioration in turbine efficiency. The loss in power is shown as a percentage of the power of four matched average engines. The nozzle flow ratio is a measure of the increase in flow obtained by trimming A8.

TABLE I
SUMMARY OF RESULTS

		T5°R	T4°R	% Ng	PT5	Nozzle Flow Ratio	ΔHP~% HP Nom
4 Matched Average Engines		1611	2225	104.15	41.98	1.0	0
Separately Ducted T5M, Trim Ng	3 Avg	1611	2225	104.15	41.98	1.0	-1.57
	1 Low	1611	2214	102.25	40.53		
T5M, Trim Ng	3 Avg	1576	2182	102.7	40.54	1.0	-6.14
	1 Low	1611	2228	102.7	40.57		
T5M, Trim A8	3 Avg	1578	2193	104.15	40.74	1.021	-3.7
	1 Low	1611	2228	104.15	40.79		
No Trim Method	3 Avg	1618	2234	104.15	42.26	1.0	+1.1
	1 Low	1653	2271	104.15	42.32		
T5M Trim Ng	4 Low	1611	2214	102.25	40.53	1.0	-6.3
T5M Trim A8	4 Low	1611	2228	104.15	40.79	1.027	-3.5

DISCUSSION OF RESULTS

In a common exhaust system, if one engine deteriorates, the effect on the overall system power is approximately the same as if all engines had deteriorated this same amount.

Using nozzle area trim reduces the power loss by 40 percent.

The effect of the 1.5 percent turbine efficiency decrease is about 1.8 times the effect of the deterioration allowed in the Monte Carlo analysis (0.5 percent ηt, 0.5 percent ηc, 0.5 percent W) and the results can not, therefore, be compared directly.

This method gives a rapid means of matching engines with an assumed deterioration. However, it can not be used to determine average or extreme expected performance in a common exhaust system. To determine this, a Monte Carlo analysis was set up as described in the next section.

MONTE CARLO ANALYSIS

General

In order to allow for engine-to-engine variation, a computer program was established. This program took the data from 29 production engines, component variation, etc., and from this deduced component variations (in compressor flow, efficiency, turbine efficiency, and T5 measurement), which were then used to construct 200 random engines. These engines were then formed into multi-engine systems, and the performance of these systems was analyzed and compared.

Method of Analysis

The steady-state maximum power output of the multi-engine system is investigated in detail employing the Monte Carlo analysis technique. In this technique, random components are computer assembled to give random engines which are then operated under various trim methods. Repetition of the calculation many times provides an estimate of the expected average and spread of system power level and engine parameters.

In Appendix I to this report is a copy of the program used for this analysis.

Production engine test data are available showing the spread in power, fuel flow (SFC), and speed under the production trim procedure, which is NG trim to constant T5M, for single engines. Component variation must be reduced from the overall performance variation since the multi-engine system will employ only the gas generator, and a knowledge of internal parameters (P5, W5, T5) is needed to determine performance in multiple arrangement.

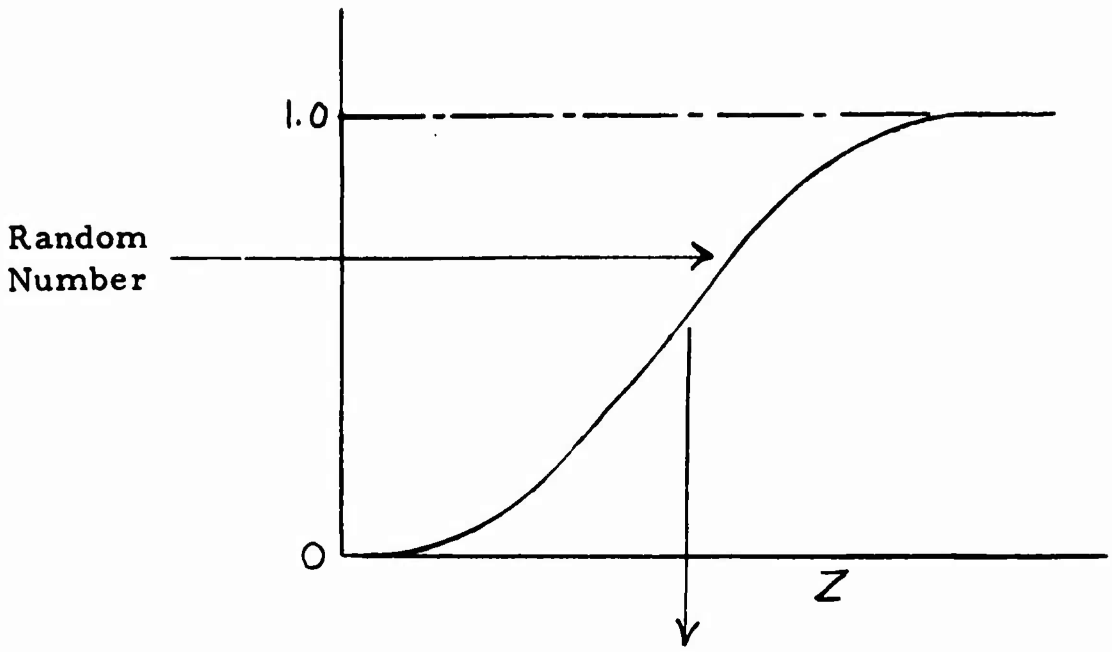
The variations used in this analysis are:

Compressor flow, $\sigma W2 = 1.0\%$
Compressor efficiency, $\sigma \eta_c = 0.40\%$
Correlation of compressor flow and efficiency, $\rho_{W_2, \eta_c} = 0.394$
Slope of correlation line $\beta_{W_2, \eta_c} = 0.917$
Turbine efficiency, $\sigma \eta t = 0.33\%$
Measured T5 correlation, $\sigma \Delta T5 = 0.6\% = 9.7°$

A random engine is found by first selecting a random number and obtaining the component deviation from normal.

For this program, a subroutine was used for generating random numbers from 0 to 1 in rectangular distribution. A normally distributed standardized variable (Z) was then found by reading from the normal cumulative distribution function, as shown in the sketch on page 14, and the normal variate was translated into the component deviation from nominal. For example,

$$\Delta W_2 = \text{Avg}\ \Delta W_2 + (Z)(\sigma W_2)$$



The effects of geometry variations (A4) and cooling and leakage flow variations were small enough to be ignored.

This process is repeated to obtain the deviations of the effective components and the influence of the component variations found by applying derivatives at constant speed. All derivatives were obtained from the Average T64 Engine Deck about the following base point.

T5 = 1611°R	NG = 104.14%
T4 = 227°R	T5M = 1611°R
W5 = 26.67 lb/sec	T4M = 2227°R
P5 = 41.95 psia	

The constant speed derivatives used are of the form

$$C_y^x = \left.\frac{\partial x}{\partial y}\right|_{Ng\ z_o}^{y_o} = \frac{\%\ \text{Change in } x}{\%\ \text{Change in } y} .$$

Those used in the analysis are given below.

$$C_{W2}^{T5} = 0.70\ ,\ C_{W2}^{T4} = 0.67\ ,\ C_{W2}^{W5} = 0.89\ ,\ C_{W2}^{P5} = 1.21\ ,$$

$$C_{\eta c}^{T5} = -1.37\ ,\ C_{\eta c}^{T4} = -1.29\ ,\ C_{\eta c}^{W5} = 0.03\ ,\ C_{\eta c}^{P5} = -0.66\ ,$$

$$C_{\eta t}^{P5} = -1.94\ ,\ C_{\eta t}^{T4} = -1.42\ ,\ C_{\eta t}^{W5} = 0.03\ ,\ C_{\eta t}^{P5} = -0.96\ .$$

The performance of each engine is found in terms of percent deviation from the base point. Thus, component variations are applied at constant speed;

for example,

$$\Delta T5M_c = C_{W2}^{T5} \Delta W2 + C_{\eta t}^{T5} \Delta \eta t + \Delta T5 .$$

If this procedure is repeated N times, we get a random sample of N engines and can find the average and variance of any parameter in the engine (T5, T5M, Ng, HP, etc.). If N is sufficiently large, this average and variance are accurate estimates of the population mean and variance.

For the multi-engine system, the engines obtained above are selected at random and combined. Each engine is adjusted in performance to achieve the required match, with the trim method being considered by the use of further derivatives. Movement along the operating line due to speed changes is found by the use of operating line derivatives,

$$R_{Ng}^{T5} = \left.\frac{\partial T5}{\partial Ng}\right|_{geom} \cdot \frac{Ng_o}{Tg_o} \quad \frac{\%}{\%}$$

$$R_{Ng}^{T4} , R_{Ng}^{W5} , R_{Ng}^{P5} ,$$

all of which are variable and are read from curves as a function of speed. Figure 10 shows these derivatives.

The adjustment in operating line level at constant speed is also accomplished by derivatives, and P5 is used as the independent variable. The three derivatives,

$$R_{P5}^{T5} , R_{P5}^{T4} , R_{P5}^{W5} ,$$

are all plotted as functions of P5 as shown in Figure 11. Movement in speed along the operating line or change in exhaust pressure to match requirement is then found as

$$\Delta T5M = \Delta T5M_c + \left(R_{P5}^{T5}\right) \Delta P5 + \left(R_{Ng}^{T5}\right) \Delta Ng .$$

As in the case of the compilation of random engines, the above process is repeated and we obtain a sample of M systems from which we can find the average and variance of any parameter.

Power output of the multiple-engine system is calculated as gas horsepower from Station 7 using flow weighted average T7 and P7:

$$HP_{gas} = W7 (H7 - H_{S9i}) .$$

Rotor horsepower and area at the rotor tip are found from the rotor performance curves shown in Figures 8 and 9. Rotor speed was fixed at 100 percent.

It can be seen that various results can be extracted from the above analysis; summarily these are:

1. Average power level for a separated exhaust system.

2. The minimum (guaranteed) and average performance of common exhaust systems as initially installed.

3. The minimum and average performance of the common exhaust systems prior to overhaul.

4. The results can be obtained for any trim method.

In obtaining the minimum and average performance prior to overhaul, engine performance was assumed to have deteriorated by 0.5 percent compressor efficiency, 0.5 percent turbine efficiency, and 0.5 percent mass flow.

The Monte Carlo technique can be classified as a brute-force method, since it relies on digital computer capabilities to "play the game" a sufficient number of times to give an accurate average and spread of performance for the common exhaust systems.

In this case, distributions of component performance were assumed to be symmetrical and uniform (actually normal), so the need for Monte Carlo analysis did not stem from odd distributions.

The problem of the multi-engine system is that the extreme engine of the group determines the performance of the remaining engines and all must match certain requirements (static pressure match and exhaust through a fixed area). An analytical approach, as opposed to the Monte Carlo method, would have been at best extremely complex with numerous assumptions and at worst not practical at all.

The Monte Carlo approach has yielded averages and variances which fit physical understanding and has allowed the investigation of many facets such as deteriorated engines and numerous trim methods.

TRIM METHODS

General

The maximum power produced by a multi-engine system will differ from the sum of separate engines because of the effects of cross communication at gas generator discharge. Thus, a high P5 engine will tend to back-pressure the remaining engines, producing overtemperature which must be relieved by the trim procedure.

The average power of N engines in a multi-engine system and the spread from system to system are of interest. Separate engines producing an average power level, μ_X, and a spread, σ_X, would be expected to give in groups of N, an average power of

$$\mu_{\bar{X}} = \mu_X$$

and have a spread in percent power of

$$\sigma_{\bar{X}} = \frac{\sigma_X}{\sqrt{N}} .$$

In multi-engine systems, the average and spread will differ from these values both because of the cross communication and because of the maximum power trim procedure employed. Three basic trim methods were investigated.

Trim NG to Maximum T5M

Throttles of all engines are advanced together until one engine indicates the maximum T5M. Topping would be set on each engine to hold this speed. The common exhaust area at the rotor tip (A8) is held constant. If translated to one engine, this method is precisely that used for present T64 production engines.

The method is simple for pilot and ground crew since topping is the only trim and all engines move together if any adjustment is made. For the method to be acceptable, the topping schedule versus T2 must be well established in order to prevent frequent retrim. We assume that the effect of multi-engine matching can be included and also that the relative position of engines will not change with T2 . If such changes occur, then reset of topping would be required.

A variation of this system has been included which assumes that T4 is the measured and displayed temperature so that trim is performed to a maximum T4M . It was found early in the analysis that this method offered no advantages over the T5 measured method, and in view of the complexity of measuring T4 , the method was not pursued.

Trim A8 to Maximum T5M

The topping schedules of all engines are set to give the same speed. All throttles are advanced to topping, and the common exhaust area at the rotor tip is trimmed until one engine indicates the maximum T5M.

The method is simple for the pilot, but ground crew must trim A8. The mechanical complexity of an area trim is introduced, although this could be as simple as tabs bolted in place.

EPR Operation

The common exhaust at rotor tip is set and fixed at a predetermined area. Throttles are ganged on all engines and are advanced until a specified value of

$$EPR = \frac{PT7}{PT2} = \frac{PT7}{P0} \quad \text{static}$$

is attained. The exhaust area must be correctly sized so that no engines are over maximum limits on speed or temperature.

The method is simple for the ground crew in that no trimming of engine or area is required. Topping would be set slightly above that speed at which engines meet EPR. However, the EPR value set by the pilot varies with T2 and the pilot must consult tables or graphs for each power setting. This complexity for the pilot might not be tolerated in a tactical mission.

The engine control could be designed to hold EPR versus T2 automatically, but present controls do not have this capability.

RESULTS FROM MONTE CARLO ANALYSIS

Table II gives the results of the steady-state analysis using the Monte Carlo technique and the trim methods described above.

DISCUSSION OF RESULTS

Summary Data

The four-engine system results are shown in Table II and compared with single-engine operation. This table illustrates the significant features of each multiple-engine system and how it differs from single-engine operation.

Table II includes data on the two-engine system and for each system shows the magnitude of the individual effects which establish minimum power level.

Note that the maximum or minimum value shown is obtained by

$$\text{Average} \pm 2\sigma$$

where σ is the best estimate from a random sample of 200 engines.

This arbitrary definition of extreme levels allows consistent comparison in all cases but may not mean exactly the same thing for all parameters and all cases since all distributions will not be the same shape. Differences of this nature should not be serious.

NG Trim, $T5M_{max}$ = 1611°R (Table II (B))

The present single-engine T64 is shipped and operated to NG trim. The three significant features of single engines versus the multiple-engine system are indicated in Table II and listed on page 21.

TABLE II
SUMMARY OF RESULTS FROM MONTE CARLO ANALYSIS

Number of Engines	HP in % of Average Power in A: Multi-Engine Effect	Operational Spread	Deterioration	$T5_{max}$ °R	T5 & $T5M_{avg}$ °R	$T5M_{max}$ °R	NG_{avg} %
	Reduction in Average Power Due to Multi-Engine Effect	Max. Variation	Variation in Average Due to Deterioration				
Format		Minimum Initial Power	Minimum Overhaul Power				
A) NG Trim to $T5M_{max}$ – Separate Engines							
1	0	±5.44	-3.5	1630	1611	1611	
		-5.44	-8.94				
2	0	±3.84	-3.5	1630	1611	1611	
		-3.84	-7.34				
4	0	±2.72	-3.5				
		-2.72	-6.22	1630	1611	1611	
B) NG Trim to $T5M_{max}$ = 1611°R							
1	0	±5.44	-3.5	1630		1611	
		-5.44	-8.94		1611		
2	-1.75	±4.34	-3.5	1626		1611	
		-6.09	-9.59		1602		
4	-2.90	±3.80	-3.50	1620		1611	
		-6.70	-10.20		1596		
C) A8 Trim to $T5M_{max}$ = 1611°R							
1	0	±3.96	-2.53	1630		1611	
		-3.96	-6.49		1611		104.14
2	-1.18	±3.20	-2.54	1626		1611	
		-4.38	-6.92		1601		104.14
4	-1.92	±2.63	-2.55	1620		1611	
		-4.55	-7.10		1595		104.14
D) EPR_1 $T5_{max}$ = 1620°R							
1	-1.75		-2.92	1630		1639	
			-4.67		1609		103.34
2	-1.62		-2.92	1626		1635	
			-4.54		1605		103.7
4	-2.10		-2.92	1620		1629	
			-5.02		1599		103.88
E) EPR_2 $T5M_{max}$ = 1611°R							
1	-5.54		-2.92	1602		1611	
			-8.46		1581		103.34
2	-4.90		-2.92	1602		1611	
			-7.82		1581		103.70
4	-4.55		-2.92	1602		1611	
			-7.47		1581		103.88

A

TABLE II
SUMMARY OF RESULTS FROM MONTE CARLO ANALYSIS

r s	HP in % of Average Power in A Multi-Engine Effect	 Operational Spread	 Deterioration	$T5_{max}$ °R	T5 & $T5M_{avg}$ °R	$T5M_{max}$ °R	NG_{avg} %	NG_{max} %
	Reduction in Average Power Due to Multi-Engine Effect	Max. Variation	Variation in Average Due to Deterioration					
t		Minimum Initial Power	Minimum Overhaul Power					
Trim to $T5M_{max}$ — Separate Engines								
	0	±5.44 -5.44	-3.5 -8.94	1630	1611	1611		105.8
	0	±3.84 -3.84	-3.5 -7.34	1630	1611	1611		
	0	±2.72 -2.72	-3.5 -6.22	1630	1611	1611		
Trim to $T5M_{max}$ = 1611°R								
	0	±5.44 -5.44	-3.5 -8.94	1630	1611	1611		105.8
	-1.75	±4.34 -6.09	-3.5 -9.59	1626	1602	1611		105.0
	-2.90	±3.80 -6.70	-3.50 -10.20	1620	1596	1611		104.6
Trim to $T5M_{max}$ = 1611°R								
	0	±3.96 -3.96	-2.53 -6.49	1630	1611	1611	104.14	104.54
	-1.18	±3.20 -4.38	-2.54 -6.92	1626	1601	1611	104.14	104.54
	-1.92	±2.63 -4.55	-2.55 -7.10	1620	1595	1611	104.14	104.54
R_1 $T5_{max}$ = 1620°R								
	-1.75		-2.92 -4.67	1630	1609	1639	103.34	104.54
	-1.62		-2.92 -4.54	1626	1605	1635	103.7	104.54
	-2.10		-2.92 -5.02	1620	1599	1629	103.88	104.54
R_2 $T5M_{max}$ = 1611°R								
	-5.54		-2.92 -8.46	1602	1581	1611	103.34	104.54
	-4.90		-2.92 -7.82	1602	1581	1611	103.70	104.54
	-4.55		-2.92 -7.47	1602	1581	1611	103.88	104.54

B

1. The average power, speed, and temperature of the multiple engine are reduced relative to the single engine.

2. The spread in speed is reduced, the spread in temperature is increased, and the spread in power is reduced.

3. The effect of deterioration equally on all engines is the same for single or multiple engines.

The reduction in average parameter levels is reasonable since the ganged throttles (all engines) are reducing speed on all engines to prevent the hottest engine from exceeding $T5M_{max}$.

The reduction in speed spread results from the cross communication of engines in the multiple system. An engine which would tend to be high in speed at T5M has good components and in the multiple system is back pressured by the poor component engine, causing the good engine to reach T5M at a lower speed. The speed spread reduction is very significant: from $2\sigma_1 = 1.66$ to $2\sigma_4 = 1.06$ percent.

The true temperature spread on single engines is due (in this analysis) only to the measuring error (T5M - T5). In multiple-engine systems, this effect is joined by a variation in T5M engine-to-engine, since the method holds only the highest temperature engine at T5M.

The interesting temperature feature is that the maximum true temperature ($T5_{max}$) is lower for the multiple system than for single engines. Thus, when operated to the same measured temperature (T5M), the multiple system is not using its design capability. An increase in $T5_{max}$ to match the single-engine value would require a higher $T5M_{max}$, which means a higher qualification temperature. Thus we see that, inherently, the qualification temperature should be set higher for multiple-engine systems than for the single-engine case. The practical considerations of qualifying on single engines, or enforcing a lower allowable temperature for single engines, and the education of the user, could be formidable.

Additional advantage for the multiple system can be gained by sizing such as to operate at NG_{max} equal to the single-engine case. The speed increase if this were done is about 1 percent. This gives about 1.9 percent in power, which would increase the minimum power of new engines in the four-engine system from 3044 to about 3100; this is <u>above</u> the minimum power for single engines.

Note that a method for deducing the required overhaul point could be devised from the amount of NG decrease for a given system. A record of NG at maximum power would be required for each system.

<u>A8 Trim, $T5M_{max}$ = 1611°R (Table II (C))</u>

The multiple system trimmed by A8 shows similar features to the NG trim results. However, in this case the speed spread is further reduced, actually existing only by the assumption that all engines would not be trimmed to exactly the same speed.

By maintaining speed and temperature, the A8 trim method achieves a significantly higher power level than the NG trim method.

Again, the $T5_{max}$ is not as high as for the single-engine case, and so there is temperature capacity which is not being used.

Similarly, the NG_{max} capability is not being used and could give even higher power level.

The unused T5 and NG capacity relative to the single-engine system is the same for the A8 trim method as shown for the NG trim, so the comparison between (B) and (C) of Table II is valid.

Note that a method for deducing the required overhaul point could be devised from the amount that A8 has been opened for a given system. A record would have to be kept with each aircraft.

EPR Operation (Table II (D) and (E))

The EPR system allows operation to a specific power level throughout engine life. Deterioration appears in temperature and speed changes rather than power changes as in the two systems previously considered. Since an engine will be removed when it indicates overtemperature or overspeed on the attempt to set power (EPR), the deterioration allowance must be built in as speed and temperature margin.

For the deterioration considered (-0.5 percent in W2, ηc, and ηt), both NG and T5 are seen to increase during the period between overhauls. At the end of the overhaul period, only the system with the worst engine will indicate an overtemperature, and many systems could be operated significantly longer. No records would be needed for overhaul conditional on performance.

Power level is set under the EPR system so that the spread in true temperature (T5) is the smallest for any of the systems. However, spread in measured temperature (T5M) is largest since the measurement inaccuracy is added to the true temperature spread. It is interesting that the temperature spread and required deterioration allowance in temperature and speed do not change with the number of engines in the system. One engine or four show the same values. Only the spread in speed changes from about 1.2 percent for single engines to 0.7 percent for the four-engine system.

Table II (D) shows results for EPR operation to the same maximum true temperature and speed as occurred for the NG and A8 trim four-engine systems ($T5_{max}$ = 1620°R and NG_{max} = 104.54 percent). Thus, (B), (C) and (D) of Table II can be compared on the basis of engine capability. Recall again that none of Table II (B), (C) and (D) utilize the capacity represented by single-engine operation.

On an equal capability basis, the EPR system is very comparable to the A8 trim system (Table II (D) versus (C)), the minimum power output being somewhat less for new engines but considerably higher for engines after deterioration.

However, if the EPR system is forced to operate to the same maximum measured temperature ($T5M_{max}$ = 1611°R) as the NG and A8 systems, then power decreases significantly and is slightly below the A8 minimum power after deterioration.

We note also that with EPR operation, minimum and average power are essentially the same; whereas for NG or A8 trim, the average system power is considerably above the minimum. Of course, the minimum level established the guarantee, not the average.

CONCLUSIONS ON RATING AND TRIM METHODS

1. Retention of the present single-engine maximum power trim (NG, T5M) for the multiple-engine case results in lower average and minimum power levels so that lower guarantee power would be available. See Table II (B).

2. The A8, T5M trim method gives somewhat higher average power than the NG, T5M method and significantly higher minimum power.

3. In the four-engine system, the minimum power per engine for the A8, T5M trim is actually higher than present single-engine (NG, T5M) minimum power but not as high as would be obtained if each engine in the group operated independently with NG, T5M trim. Compare (A) and (C) of Table II.

4. If trimmed to present single-engine maximum measured temperature (T5M), both NG and A8 systems do not utilize full engine temperature capability. See $T5_{max}$ for single- versus four-engine system in Table II.

5. Component deterioration, equal on all engines, gives the same power loss per engine on multiple-engine systems with NG, T5M trim as now is seen for single engines. See Table II.

6. Component deterioration, equal on all engines, gives less power loss on the A8, T5M trim than on the NG, T5M trim.

7. Four-engine EPR_1 operation such that the maximum true engine temperature ($T5_{max}$) is equal to that seen in the NG or A8 methods gives a minimum power level after deterioration slightly less than the A8, T5M trim minimum power before deterioration, but greater than A8, T5M after deterioration.

8. The EPR_1 method gives $T5_{max}$ only on the worst engine after deterioration.

9. The EPR_1 method requires a maximum measured temperature ($T5M_{max}$) somewhat higher than used in the NG, T5M and A8, T5M methods. That is, the qualified temperature ($T5M_{max}$) must be higher.

10. Four-engine EPR_2 operation such that the maximum measured temperature ($T5M_{max}$) is equal to that used in the NG or A8 methods gives minimum power level after deterioration slightly below the A8, T5M method after deterioration.

11. EPR_2 operation gives a maximum true engine temperature ($T5_{max}$) significantly lower than any other trim method.

RECOMMENDATIONS FOR RATING AT TRIM METHOD

1. The A8, T5M trim is significantly superior to the NG, T5M trim in power capability but introduces some added complexity in requiring A8 trim. However, trim of A8 by tabs or screw adjustment of exit vanes appears practical such that the A8, T5M trim is recommended over the NG, T5M trim.

2. The EPR method, if operated to engine capability ($T5_{max}$), would allow the highest guarantee power after deterioration of any method considered. However, the qualified temperature ($T5M_{max}$) must be higher than the other methods because the difference between measured and true temperature (T5M - T5) has different influence for EPR methods versus methods holding T5M.

   On the basis of engine capability (T5 true), the EPR method deserves serious consideration. The average power will be lower than A8, T5M but the guarantee (minimum) power will be about equal to the A8, T5M method for new engines and significantly better for deteriorated engines.

SYSTEM VARIATION

General

Where applicable in these analyses, the hot gas cycle rotor has been considered as the aircraft configuration. An explanation of this system is, therefore, required together with some comments concerning other systems.

Hot Gas Cycle Rotor

With this system, the exhaust nozzles are choked and this condition establishes the Mach number levels in the rotor ducting. This Mach number level and the flow path establish the friction, diffusion and expansion losses in the rotor, all of which vary approximately with the dynamic head (i.e., M^2). To counter these losses, centrifugal pumping occurs when the rotor is spinning such that the pressure rise, due to pumping, is approximately equal (for the XV9A system which has been used here) to the pressure drop due to friction, etc. The net result is that engine exhaust pressure approximately equals rotor nozzle inlet pressure at 100 percent rotor speed. Any increase in Mach number in the ducting, such as would occur if the nozzle was opened, causes the friction drop to increase as the Mach number squared. The pumping rise remains constant, such that overall ΔP increases steeply from 0 as tip nozzle area opens. The reduced pressure then lessens the increased flow ($W\sqrt{T}$) such that while power should increase with higher flow, it also should decrease for lower available pressure ratio. Only a fraction of the power potential is thereby realized. This fraction depends upon the rotor sizing (i.e., upon rotor duct Mach number) and upon the pressure ratio level, since gas horsepower/pound of flow is not linear with pressure ratio. Figures 8 and 9 show the nozzle and rotor characteristics.

Cruise Fans and Lift Fans

Existing cruise fans and lift fans use partial arc admission; therefore, there would be no feedback between engines.

Jet Nozzle

The comments concerning pressure loss for the ducted fan apply with the jet nozzle.

POWER EXTRACTION

General

The extraction of auxiliary power is a consideration under all engine operating conditions; therefore, it must be viewed not only as a limitation to available maximum power but also as a penalty to fuel consumption during a mission. Several methods of extracting power can be considered:

1. Power extraction from the aircraft rotor.

2. Power extraction by bleeding the exhaust gas stream after mixing to drive an auxiliary turbine.

3. Extracting power from individual gas generators through accessory gearboxes.

4. Extracting power through compressor discharge bleed manifold to an auxiliary turbine.

A number of engines installed in a common exhaust system will be trimmed up such that maximum allowable T5 is held on the hottest engine. When accessory power is extracted, depending upon the means used, various rematchings occur affecting available power by different degrees.

Aircraft Rotor Shaft

When power is drawn directly from the helicopter rotor, a collective pitch reduction should occur commensurate with the accessory power demand. No pilot action is required to prevent overtemperature, regardless of power extraction levels, since engine operating point is not affected and since a penalty of 1.0: 1.0 is incurred. That is to say, for every horsepower extracted, the power to the rotor is reduced by the same amount.

The SFC penalty is in direct proportion to the power extraction, provided the pilot reduces collective pitch. At a part-power condition, the rotor speed governor increases gas generator power to make up the lost rotor speed. This reduces the SFC penalty to 0.8 percent/percent horsepower extracted at maximum power and 0.6 percent/percent horsepower extracted at 33 percent maximum power.

Common Exhaust Bleed

When the common exhaust is bled to power an auxiliary turbine, the engine and nozzle are mismatched by the percentage of air being bled. If the nozzle is sized for the no-extraction condition, when the accessory drive comes on line, it acts like an increase in nozzle area. The magnitude of the increase depends upon pressure drop to the auxiliary turbine diaphragm and the percentage of air being bled. Since the engines see a larger exhaust area, the corrected flow must increase or the back pressure must decrease in order to satisfy exhaust continuity. If PLA is held (i.e., on topping with no speed or flow increase allowed), the pressure will be reduced. Since a lower back pressure would tend to accelerate the gas generators at the initial temperature levels, T5 must come down, which in turn forces P5 down further to maintain continuity. Since P5 drops more rapidly than T5, the situation stabilizes at about a ratio of 1.6:1; i.e., for every 1 percent of exhaust bleed, a corresponding 1.6 percent reduction in back pressure occurs (where auxiliary turbine nozzle pressure and exhaust nozzle pressure are equal). Since the partial of power with respect to P5, $\left.\frac{\partial HP}{\partial PT5}\right|_{A8=C}$, is 2.0 percent/percent, the reduction in power would be approximately 3.20 percent per percent of exhaust bleed. At part power, because T5 has been reduced (approximately 1.1 percent per percent bleed), an increase in gas generator speed can be made until maximum allowable T5 is reached on the hottest engine (approximately 0.7 percent NG per percent exhaust bleed). This would restore pressure and cause no power loss regardless of power extracted. The SFC would increase directly with the percentage of air being bled. This would hold true at part power as well (i.e., SFC at constant horsepower increases directly with percent exhaust bleed flow).

The sizing of exhaust area becomes critical when large percentages of exhaust gas are being drawn. Large overspeeds can occur if the nominal speed is close to maximum allowable. It may become necessary to undersize the exhaust area so that the large area increase when the accessory turbine comes on line does not drive the engines overspeed or cause a significant power reduction.

Accessory Gearbox

Power extraction through the accessory gearbox behaves like compressor deterioration; and since the power must be drawn from individual engines, the risk of mismatching the extractions is present. When the power extraction is balanced, the engines must be throttled back in order to reduce the flow. This is because the extraction has necessitated increased turbine work per pound of flow, which would cause overtemperature if no corrective action was taken.

Assuming that all the engines are matched, the power penalty is about 2.5:1 and the increase in SFC is about 1.7 percent per percent horsepower extracted.

Unbalanced power extraction of this kind acts like unbalanced compressor deficiency, and the pilot should endeavor to balance the extraction. However, if this is not done and the engines are at topping, the pilot may take corrective action by retarding all the engines as in the NG trim method. This latter action results in a large power loss of 10.0:1. Due to the variable nature of the unbalance, A8 trim can not be used as in the case of a compressor deficiency.

Compressor Discharge Bleed

Driving an auxiliary turbine with compressor discharge bleed also presents the risk of mismatching bleed. Because of the high pressure supply, a multi-stage turbine would be required; and due to the low mass flow, this would result in a poor efficiency.

The engines would respond to the reduced gas generator flow by increasing temperature, a 1 percent flow increasing T4 by 16°F. If this temperature increase is allowed as at low powers, the power loss is 0.6 percent per percent bleed. At topping, however, the engines must be throttled back so that the power penalty is approximately 3.1 percent per percent bleed.

The SFC penalty is of the order of 2.4 percent per percent bleed.

Assuming 100 percent turbine efficiency, the horsepower equivalent of 1 percent of compressor bleed is 52 horsepower per percent bleed.

Overtemperature induced by unbalanced bleed is the one overtemperature condition which is aggravated by a common exhaust system. In an unbalanced bleed situation, the energy demand on the high bleed engine turbine is increased. In the separately ducted case, the reduced turbine flow can be accompanied by a proportionally reduced back pressure (for nozzle continuity) such that only a small portion of the higher work per pound need be accounted for by increasing temperature.

In the common exhaust situation, a change in flow on one engine appears 1/nth as great for the system of n engines. For the four-engine case, this means that back pressure will be reduced by only 1/4 of the unbalanced bleed. The high bleed engine must, therefore, make up the deficiency and work per pound by going up in temperature somewhat further than would have been necessary had it been separately ducted.

The desired corrective action is again to eliminate the mismatch; but if this is not done, the throttle setting may be reduced with the ensuing large power loss 12.5 percent per percent bleed.

TABLE III
EFFECTS OF CUSTOMER POWER EXTRACTION

Extraction Means	SHP Penalty
Rotor Shaft	1:1
Balanced Accessory Gearbox	2.5:1
Balanced Compressor Discharge Bleed	3.3:1
Common Exhaust Bleed	3.5:1
Unbalanced Accessory Gearbox	10:1
Unbalanced Compressor Discharge Bleed	13.3:1

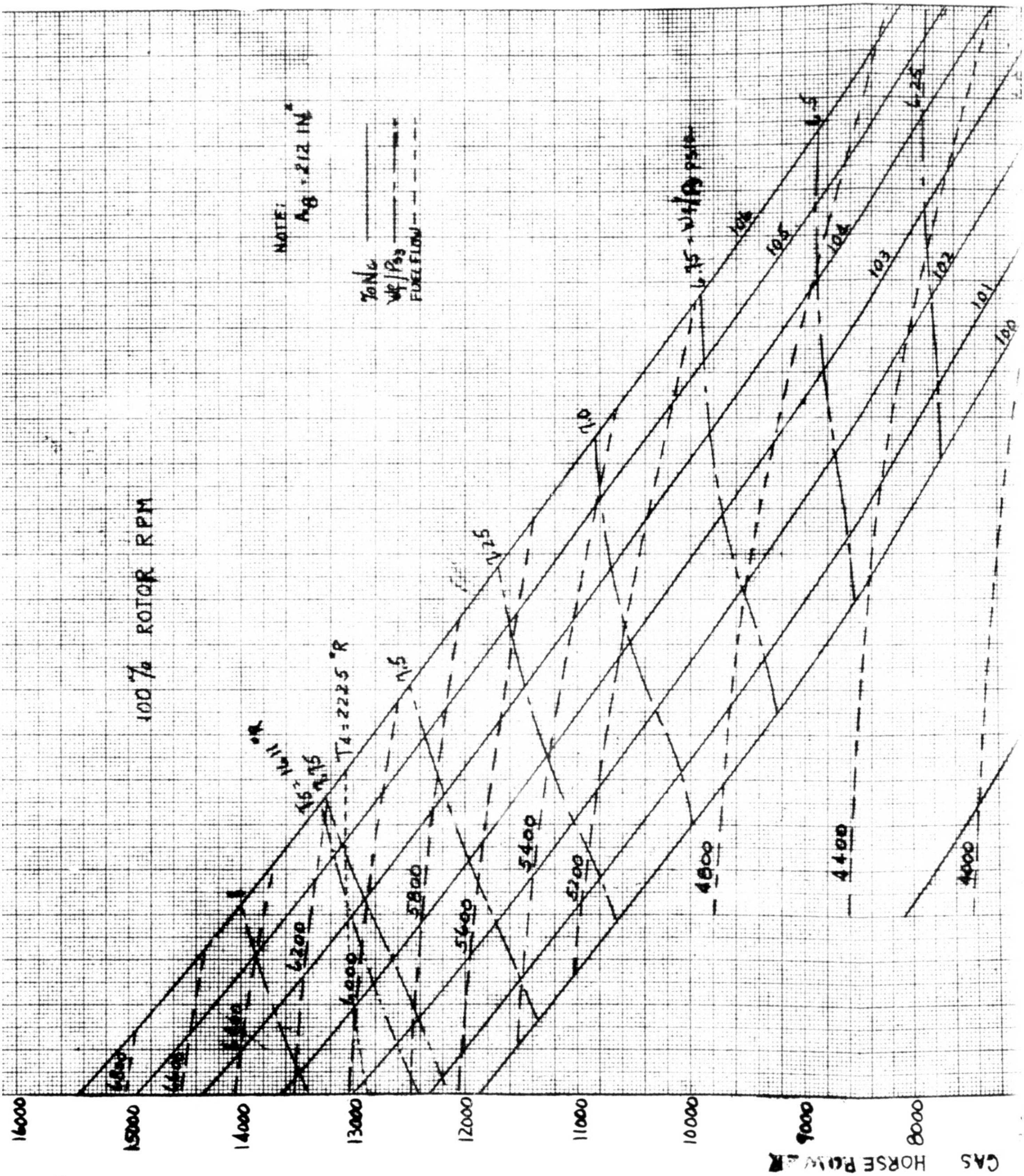
It should be noted that in the cases of unbalanced bleed or accessory power extraction, the performance penalties shown in Table III are for the worst case, i.e., drawing all power from the poorest engine. Also, it was assumed in the case of compressor discharge bleed that the utilization efficiency is 60 percent; in the case of common exhaust bleed, the utilization efficiency was assumed to be equal to rotor efficiency.

Conclusions and Recommendations

The results shown summarily in Table III indicate that the best means of obtaining power is obviously to take it from the rotor shaft. This may be difficult to obtain and undesirable at low rotor speeds.

In view of this, it is recommended that if shaft power is required, it should be taken in the form of balanced extraction from the accessory gearboxes.

If the power is required as gas power, then the choice between common exhaust and balanced compressor discharge bleed would depend upon its mode of use.



100 % ROTOR RPM
NOTE:
%Ng
FUEL FLOW
T4 = 2225 °R
GAS HORSE POWER
16000
15000
14000
13000
12000
11000
10000
9000
8000
100
101
102
103
104
105
106
4000
4400
4800
5200
5400
5600
5800
6000
6200

A

B

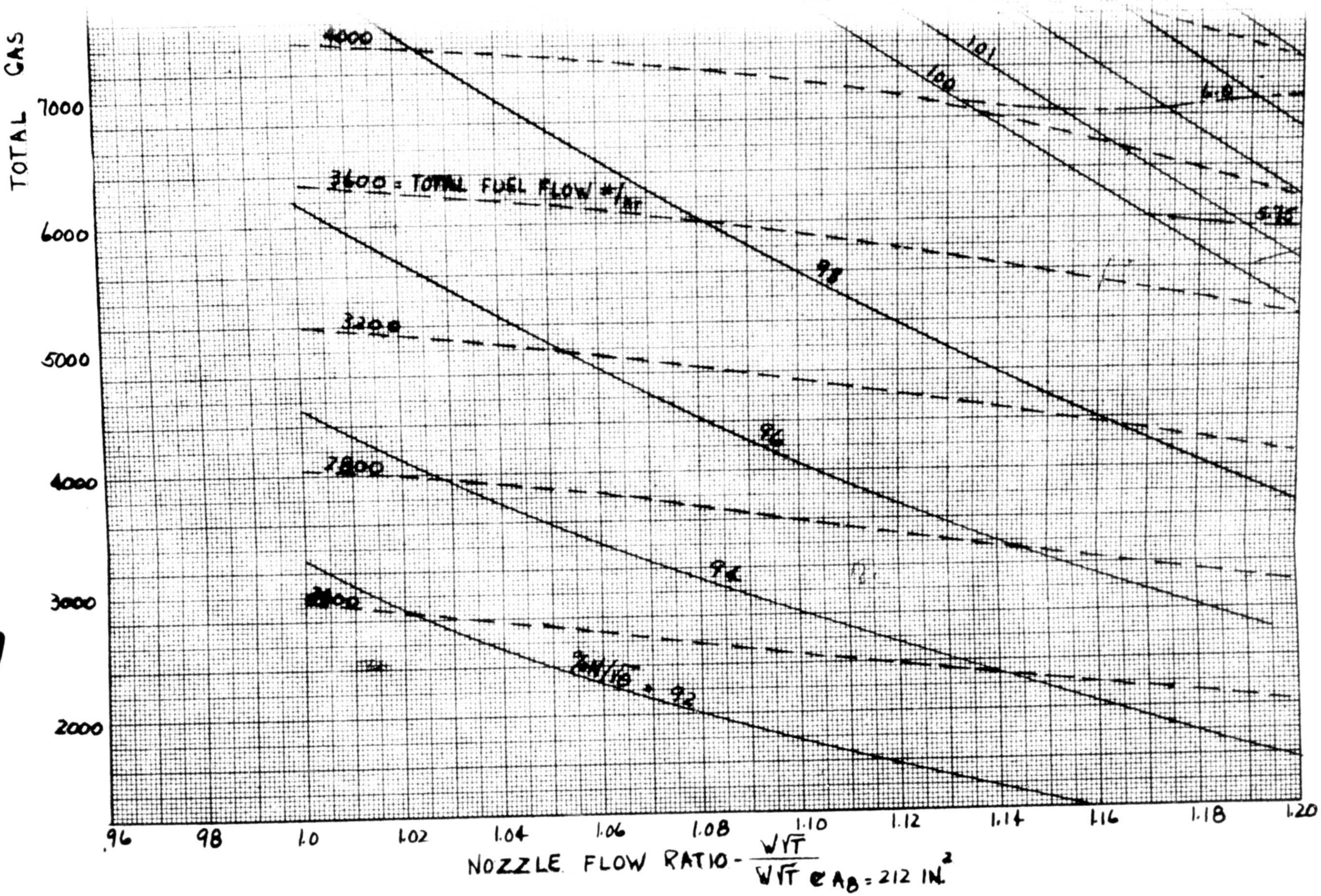
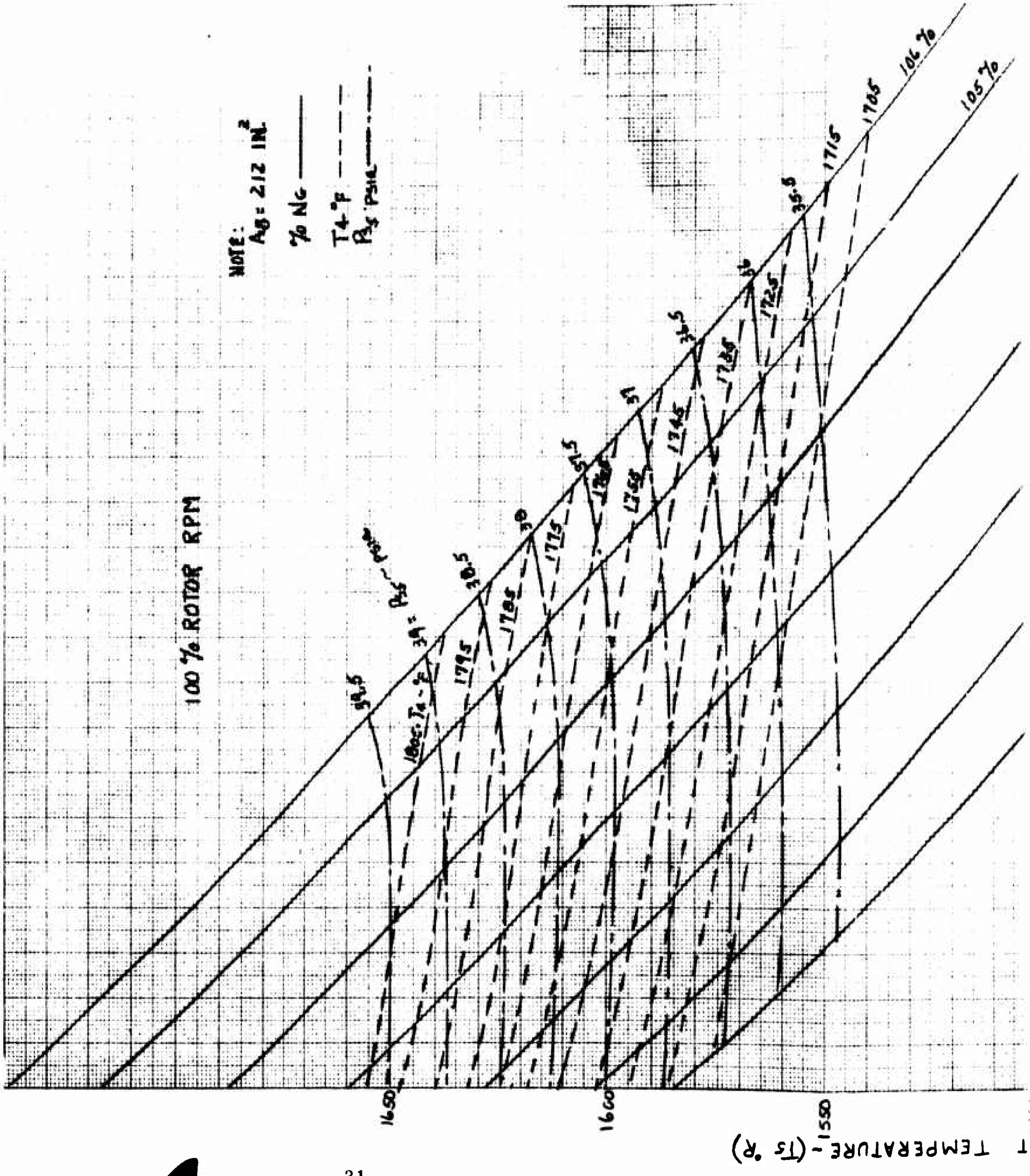


Figure 1. Estimated Steady-State Performance – Good Engine; Total Gas Horsepower vs Rotor Flow Capacity Ratio


100 % ROTOR RPM
NOTE:
A_8 = 212 IN²
% NG
T4 °F
P_5 PSIG
106 %
105 %
1650
1600
1550
TEMPERATURE - (T5 °R)

A

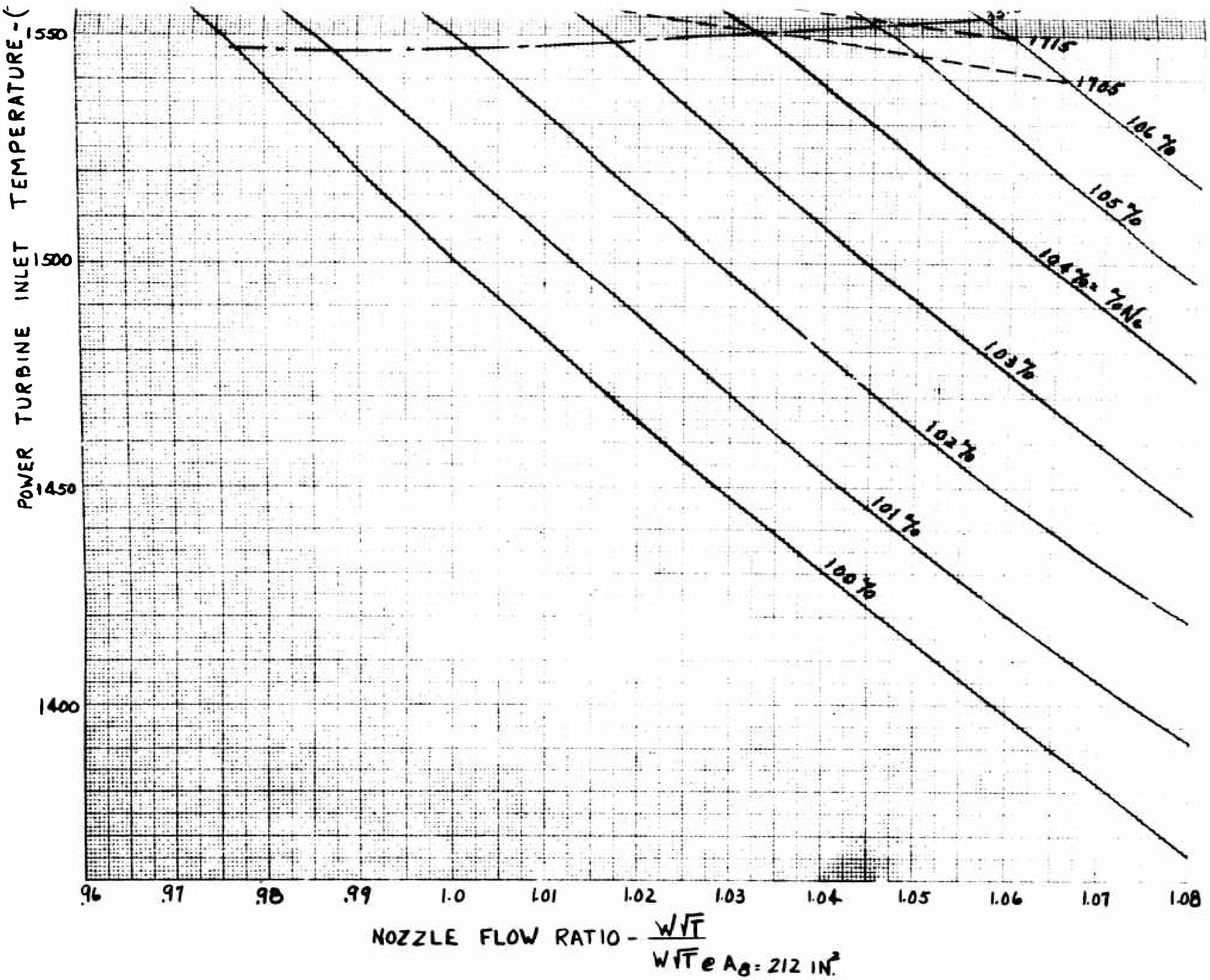
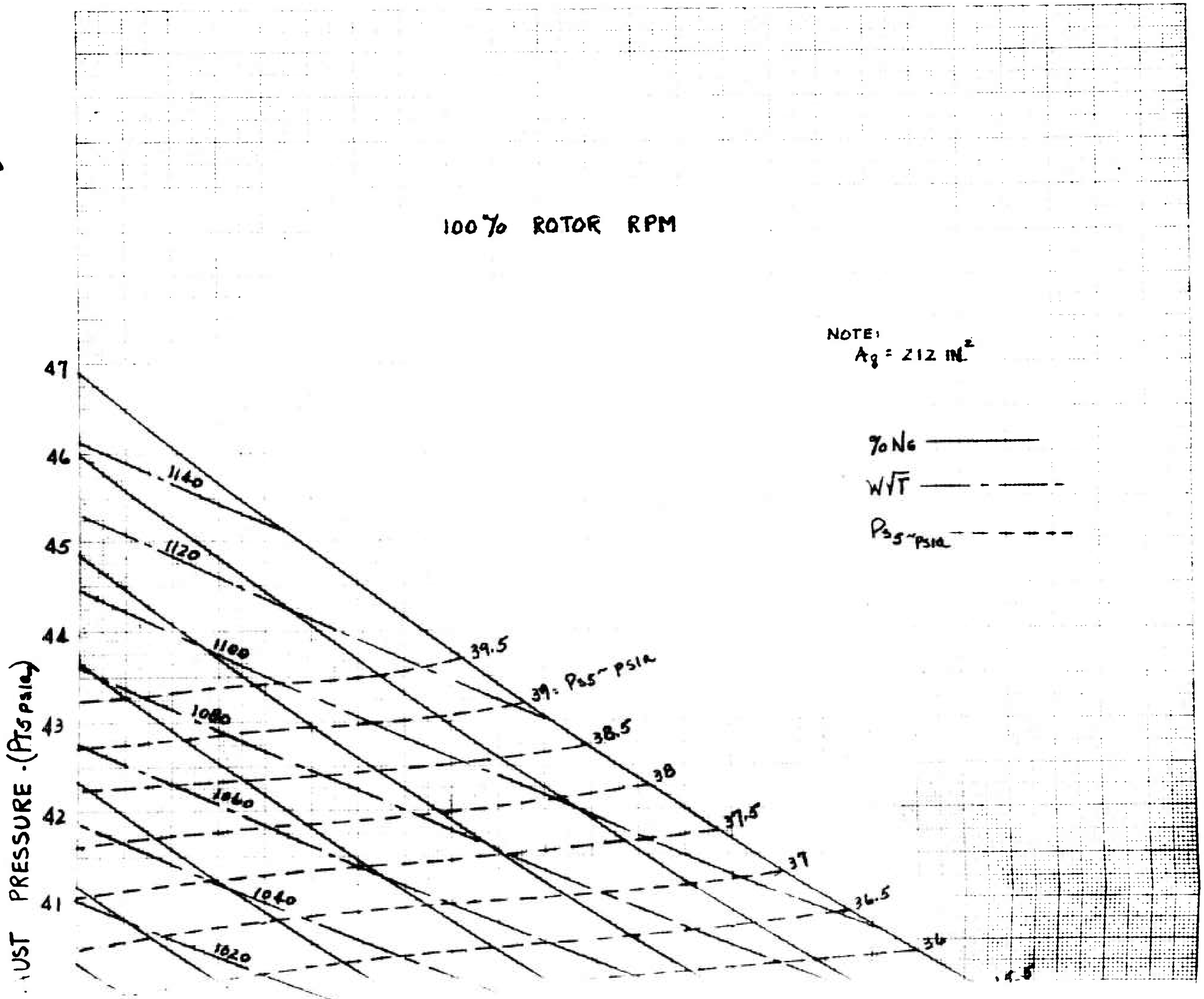


Figure 2. Estimated Steady-State Performance – Good Engine; Matching Characteristic of NG, PS5, T4, T5 vs Rotor Flow Capacity Ratio

B



100% ROTOR RPM
NOTE:
A_8 = 212 IN²
%N_G
$W\sqrt{T}$
P_{35}~psia
39.5
39 = P_{35}~psia
38.5
38
37.5
37
36.5
36
1140
1120
1100
1080
1060
1040
1020
47
46
45
44
43
42
41
UST PRESSURE - (P_{T5} psia)

A

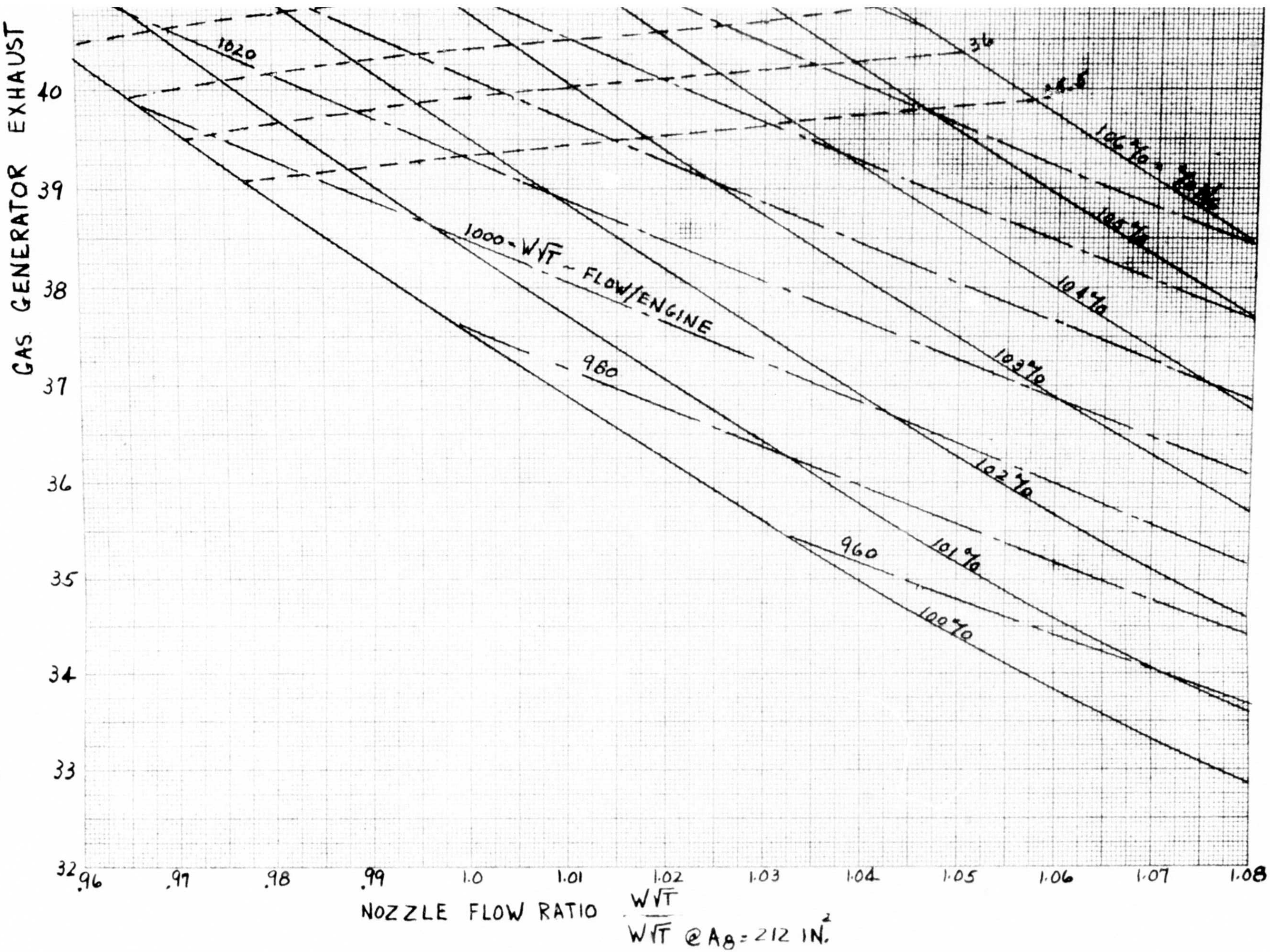
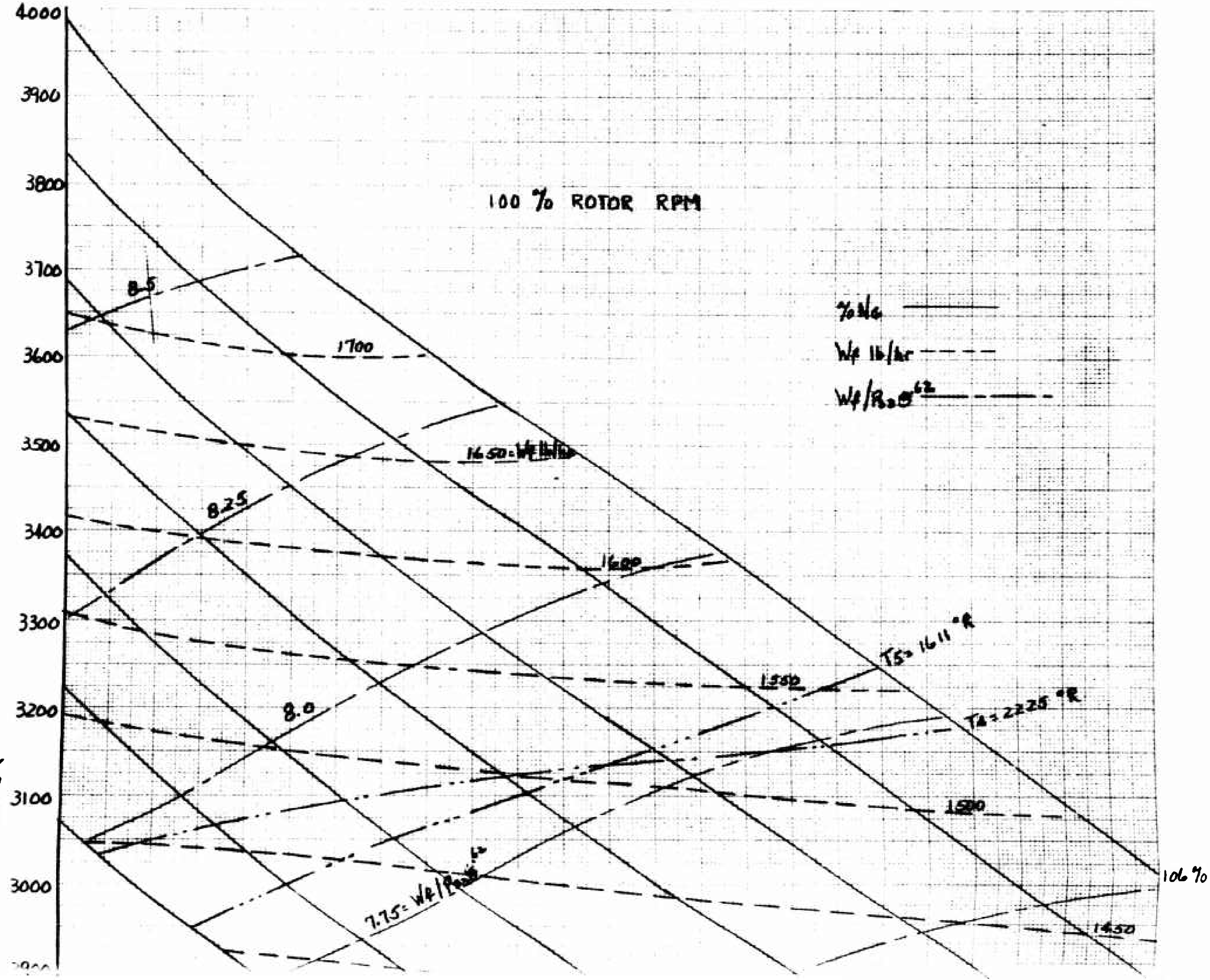


Figure 3. Estimated Steady-State Performance – Good Engine; Matching Characteristic of NG, PS5, PT5, $W\sqrt{T}$ vs Rotor Flow Capacity Ratio


100 % ROTOR RPM
%N_G ———
Wf lb/hr - - -
Wf/$P_{2}\theta^{.62}$ — - —
4000
3900
3800
3700
3600
3500
3400
3300
3200
3100
3000
AS HORSEPOWER
8.5
8.25
8.0
7.75 = Wf/$P_{2}\theta^{.62}$
1700
1650 = Wf lb/hr
1600
1550
1500
1450
T5 = 1611 °R
T4 = 2225 °R
106 %

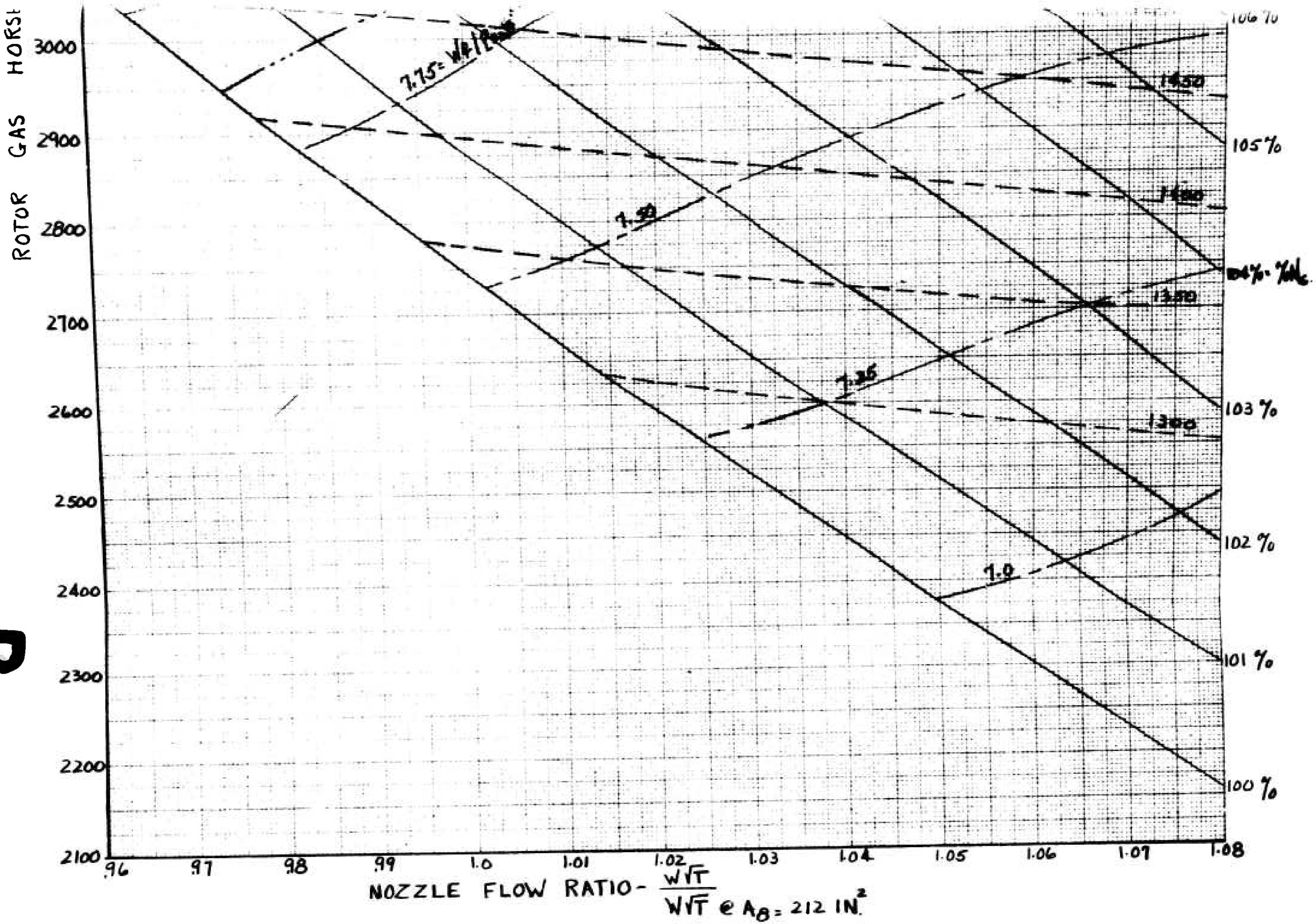
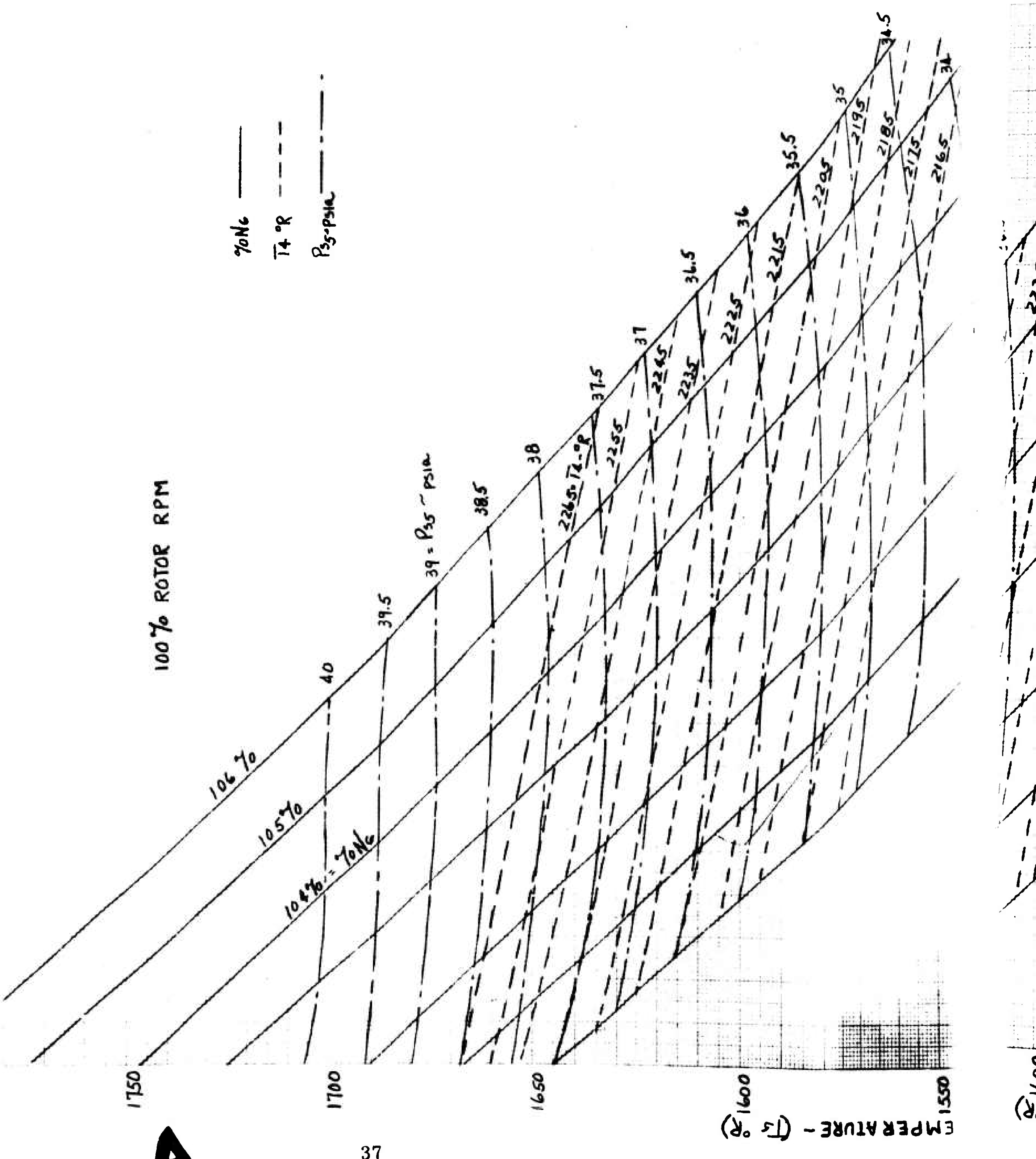


Figure 4. Estimated Steady-State Performance – Poor Engine;
Total Gas Horsepower vs Rotor Flow Capacity Ratio



100% ROTOR RPM
%NG
T4 °R
P35-psia
106%
105%
104% = %NG
40
39.5
39 = P35 ~ psia
38.5
38
37.5
37
36.5
36
35.5
35
34.5
34
2265 = T4 - °R
2255
2245
2235
2225
2215
2205
2195
2185
2175
2165
1750
1700
1650
1600
1550
EMPERATURE - (T5 °R)

A

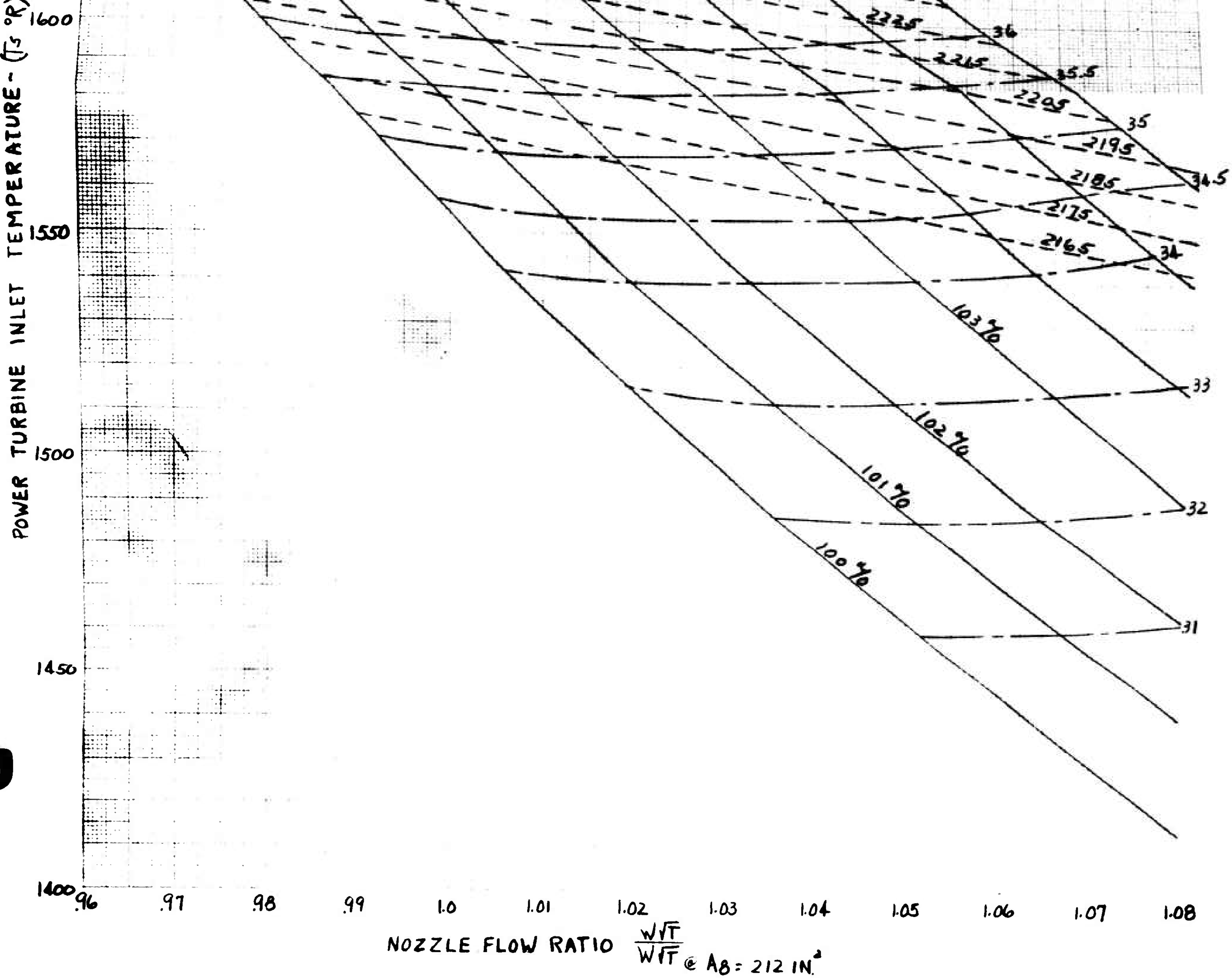
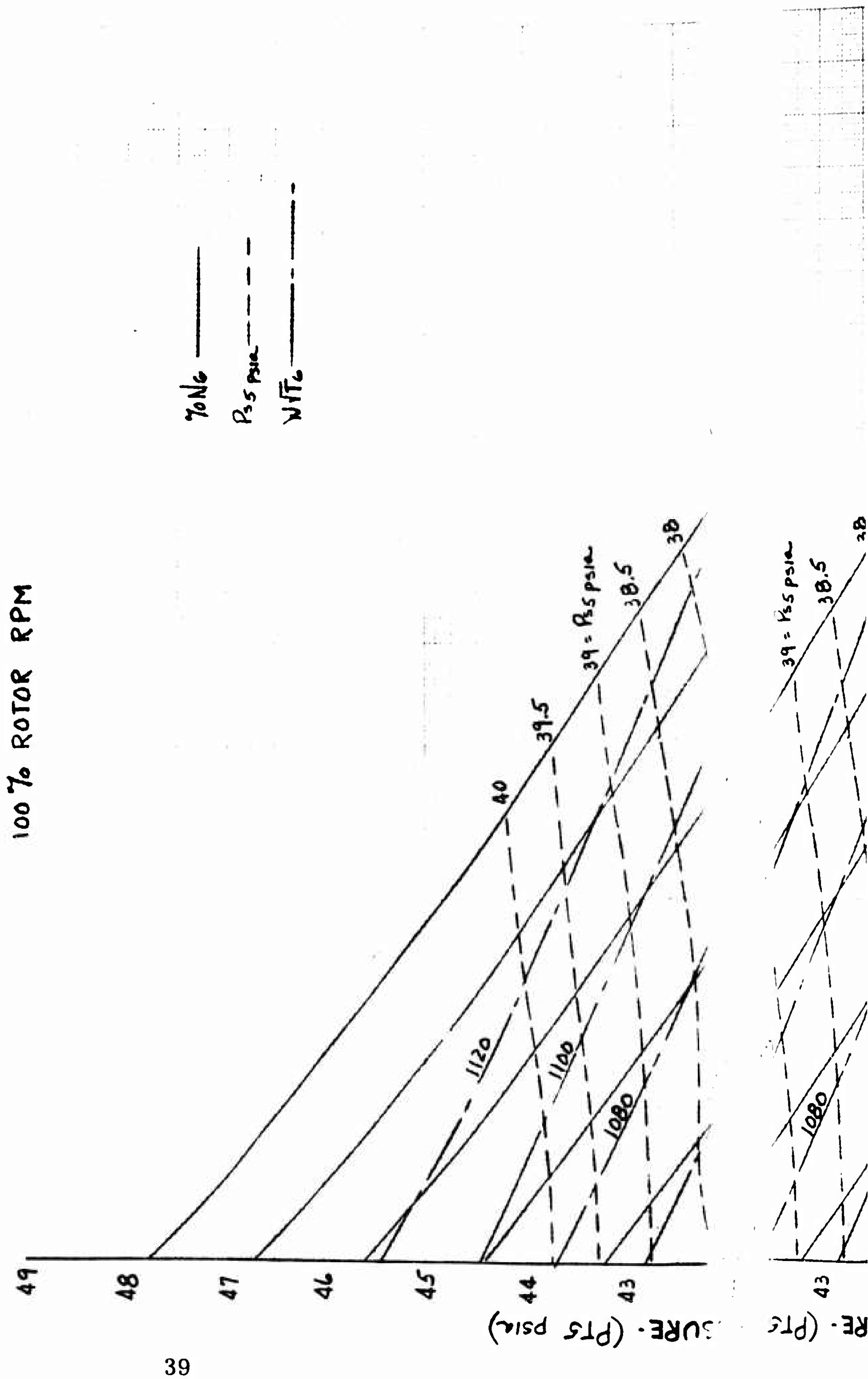
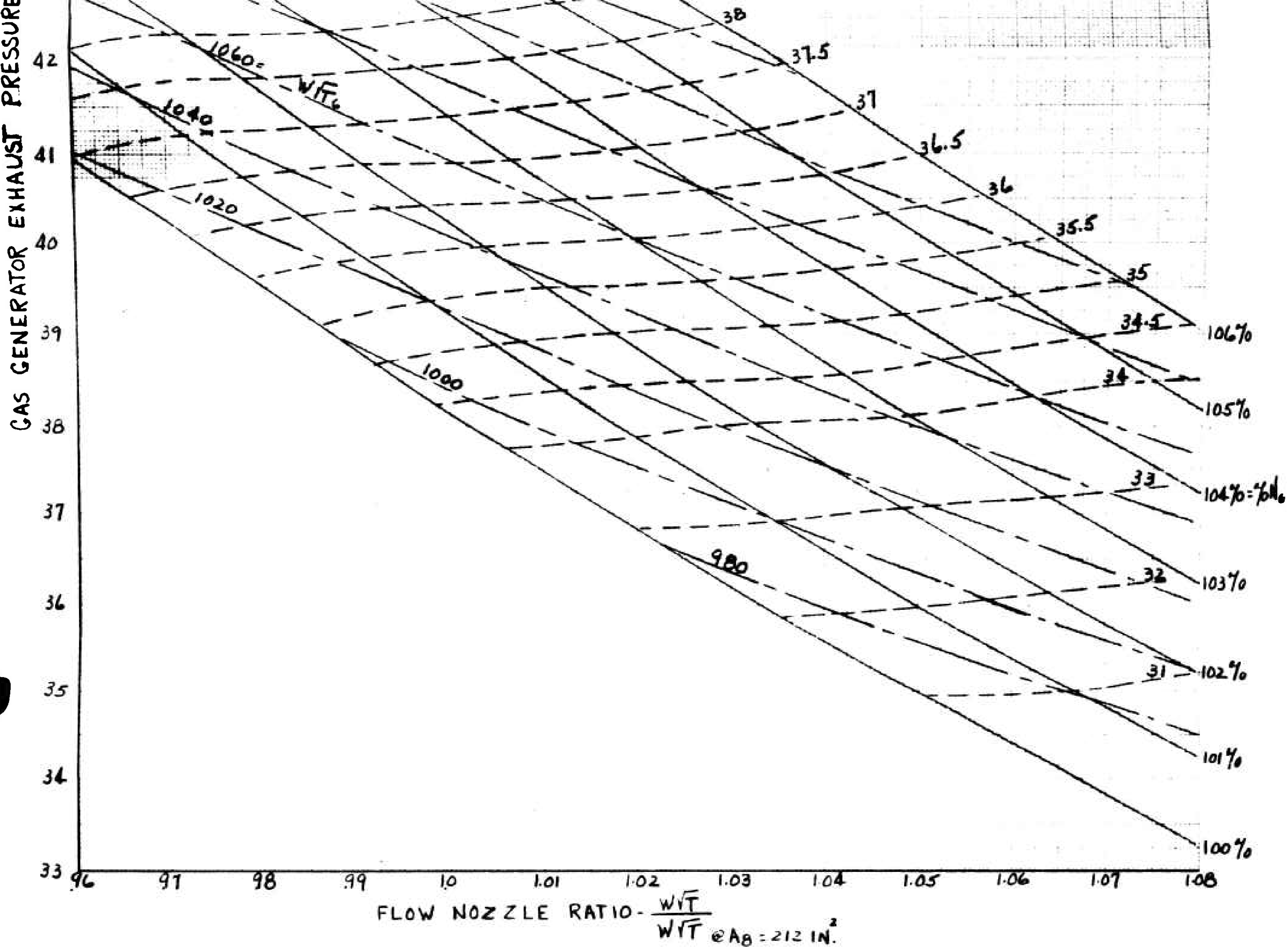


Figure 5. Estimated Steady-State Performance – Poor Engine; Matching Characteristics of NG, PS5, T4, T5 vs Rotor Flow Capacity Ratio

B


100 % ROTOR RPM
%NG
Ps5 psia
N√T6
40
39.5
39 = Ps5 psia
38.5
38
1120
1100
1080
49
48
47
46
45
44
43
SURE · (PT5 psia)

A



B

Figure 6. Estimated Steady-State Performance – Poor Engine; Matching Characteristics of NG, PS5, PT5, $W\sqrt{T}$ vs Rotor Flow Capacity Ratio

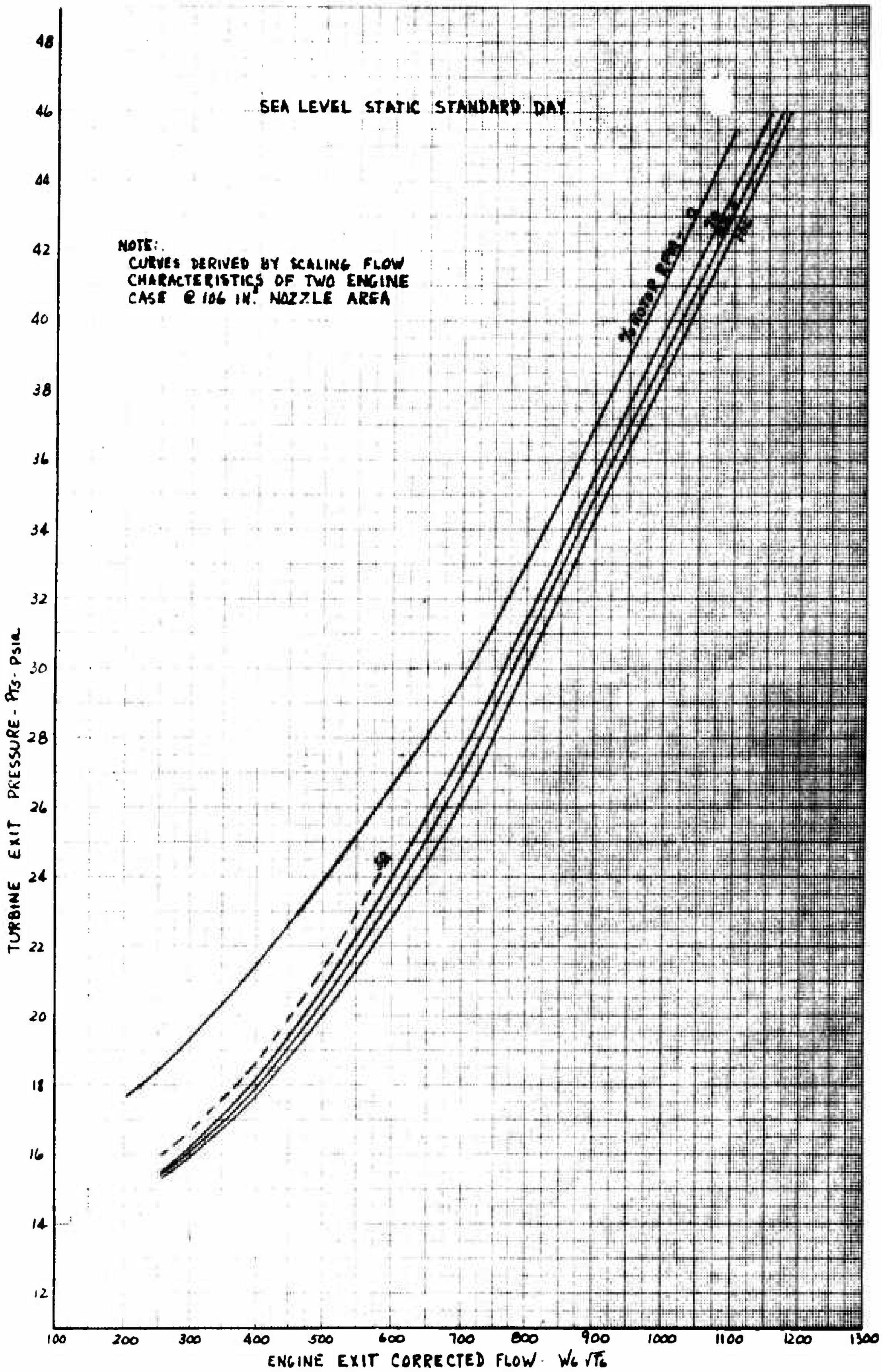


Figure 7. Multiple-Engine Common Exhaust Hot Cycle Rotor Helicopter; Nozzle Characteristic

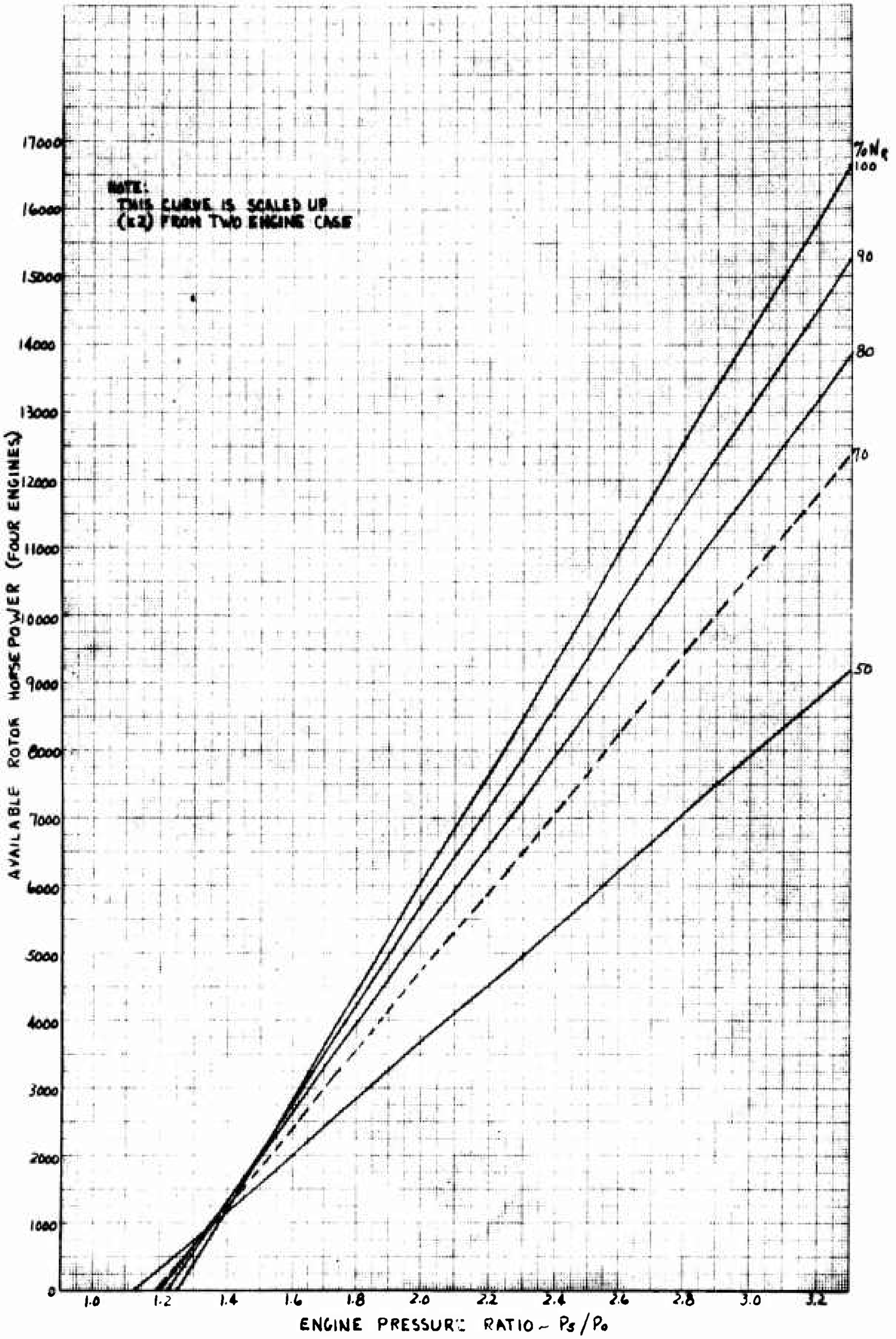


Figure 8. Multiple-Engine Common Exhaust Hot Cycle Rotor Helicopter; Estimated Horsepower Available vs Engine Pressure Ratio

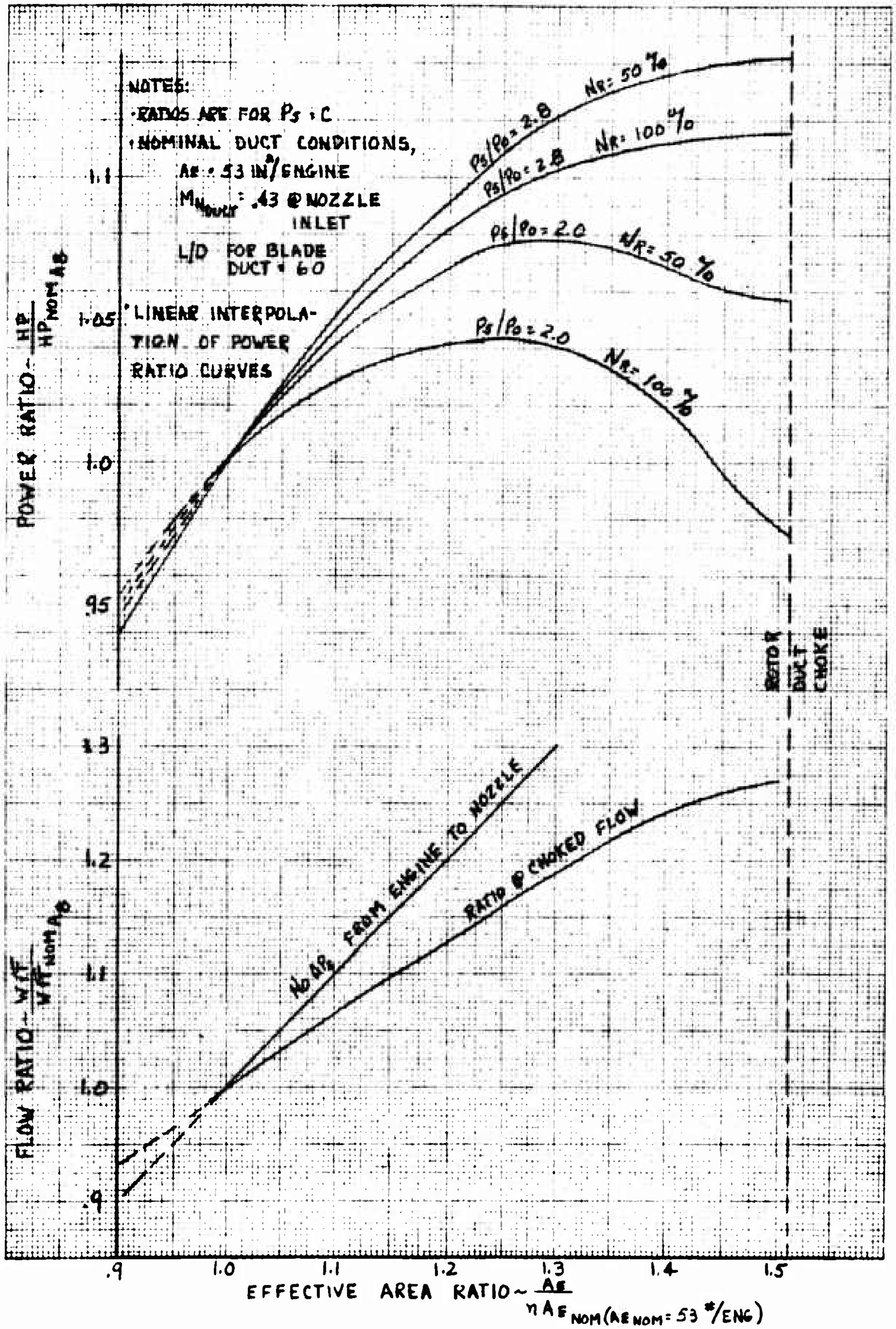


Figure 9. Effects of Tip Nozzle Effective Area on Flow Characteristics and Performance

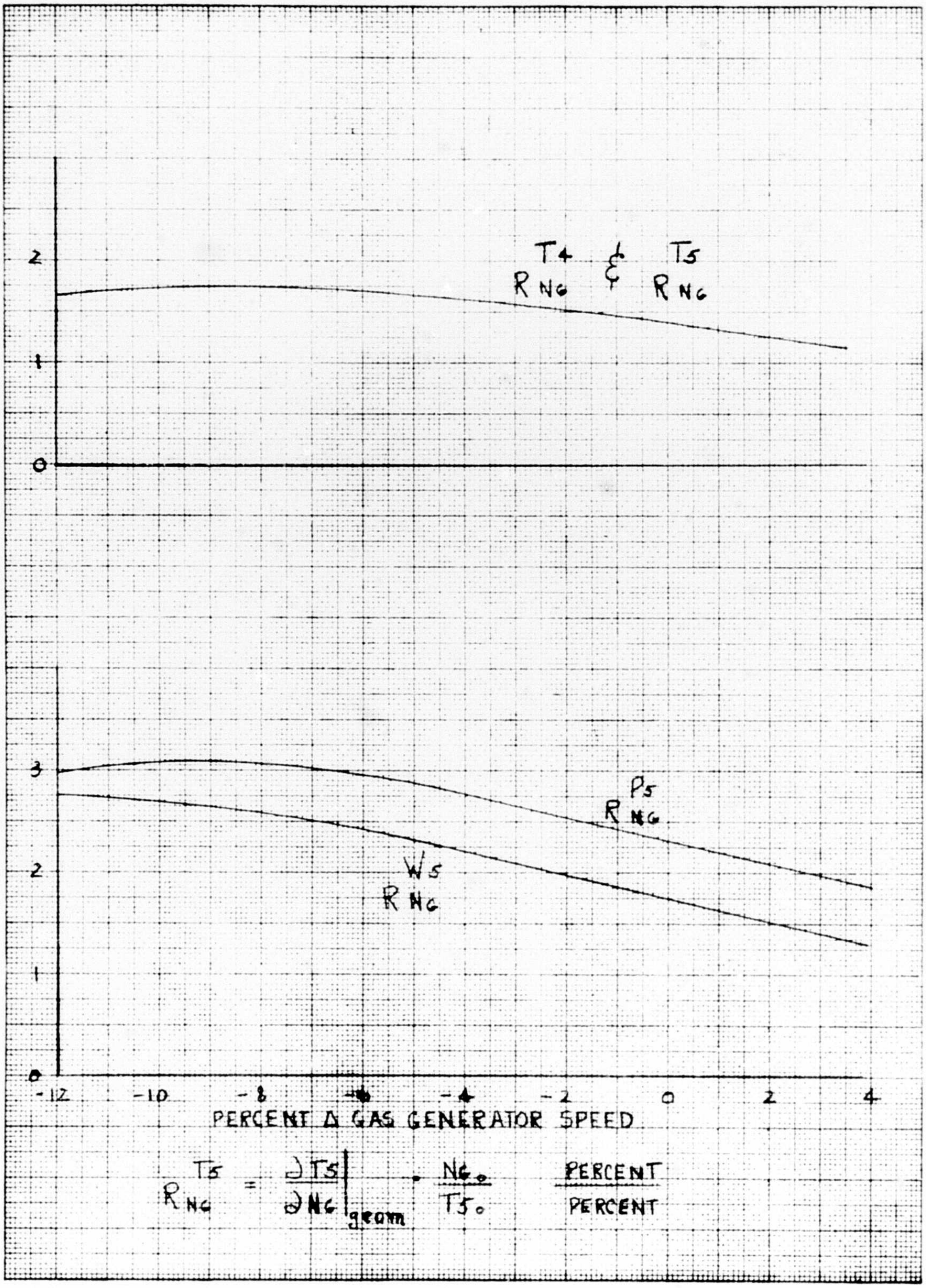
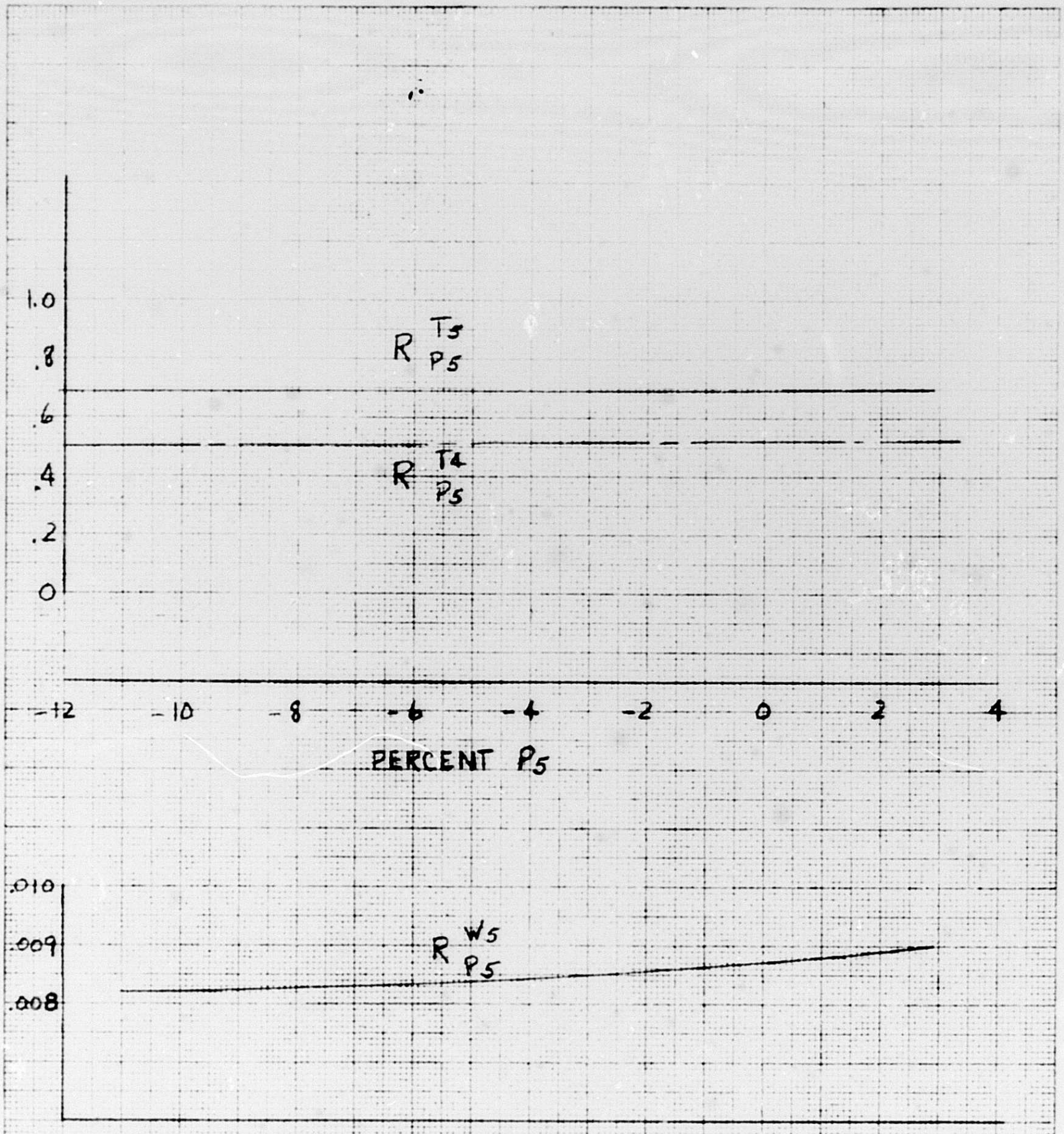


Figure 10. T64 Speed Derivatives



$$R^{T5}_{P5} = \left.\frac{\partial T_5}{\partial P_5}\right|_{N_G} \cdot \frac{P_{5_0}}{T_{5_0}} \qquad \frac{\text{PERCENT}}{\text{PERCENT}}$$

Figure 11. T64 Exhaust Pressure Derivatives

TRANSIENT PERFORMANCE

INTRODUCTION

The purpose of this section is to describe the means by which the transient controls were established and analyzed. The investigation of the transient performance was conducted on a digital computer using the Dynamic Systems Analyzer (DYNASAR) program. A copy of this program is included in Appendix II.

DYNASAR is a digital computer program for the study of dynamic systems, and it uses simulation and response techniques similar to those used in the analog computer. It is suitable for the evaluation of large, complex linear and nonlinear systems which are describable by differential equations.

The systems model used in this study comprises four T64 gas generators, each of which is represented by a nonlinear block diagram (Figure 12), a fuel control (Figure 13), and an engine exhaust diverter valve (Figure 14). The remainder of the system is represented by the aircraft ducting (Figure 15), a hot gas cycle rotor (Figure 16), and a transient speed coordinator (Figure 17). The block diagram for the variable tip nozzle area A8 is shown in Figure 18. The dynamics of this system are not included in the DYNASAR program in Appendix II, since the system was rejected early in the analysis.

The system block diagrams are a combination of the various types of operational blocks as used in analog computers.

Using the DYNASAR program, it is possible to determine the effects of various modes of mismatch on the transient performance of the system.

A linear stability study of the four-engine case was conducted to determine the actual governing requirements.

DESCRIPTION OF FUNCTIONS

The following is a definition of the various constants and functions used in the system:

Dn = A diverter function for the nth engine
Dn = 1 if the engine exhaust is diverted
Dn = 0 if the engine exhaust is not diverted

ΔT = A time delay used to determine the effects of delayed diverter operation on system performance (sec)

K_1 = A constant used to bias the fuel control acceleration schedule
$K_1 = 1.0$ for nominal operation

K_2 = A constant used to bias the engine steady-state line
$K_2 = 1.0$ for nominal operation

K_3 = A constant used to bias the unbalanced gas generator torque
$K_3 = 1.0$ for nominal operation

K_4 = A constant used to bias the engine air flow
$K_4 = 1.0$ for nominal operation

K_5 = A constant used to bias the effect of unbalanced torque on engine exhaust temperature
$K_5 = 1.0$ for nominal operation

K_6 = A constant used to bias the engine exhaust temperature
$K_6 = 1.0$ for nominal operation

K_7 = A constant used to simulate the volume of the aircraft ducting

K_8 = A constant used to bias the engine steady-state line
$K_8 = 0$ for nominal operation

K_9 = A constant used to bias the aircraft ducting pressure losses
$K_9 = 1.0$ for nominal operation

K_{10} = A constant used to select the mode of rotor speed control
$K_{10} = 1.0$ if load signal compensation is used
$K_{10} = 0$ if load signal compensation is not used

F_1 = Wf/PS3 vs PLA

F_2 = Temp reset Wf/PS3 vs % Ng & θ

F_3 = Acceleration $Wf/PS3\ \theta^{.62}$ vs $\%\ Ng/\sqrt{\theta}$

F_4 = Steady state $Wf/PS3\ \theta^{.62}$ vs $\%\ Ng/\sqrt{\theta}$ & $\frac{PT5}{\delta}$

$F_5 = \frac{Wg\sqrt{\theta}}{\delta}$ vs $\%\ Ng/\sqrt{\theta}$ & $\frac{Wf}{PS3\ \theta^{.62}}$

$F_6 = \frac{TT5}{\theta}$ vs $\%\ Ng/\sqrt{\theta}$ & $\frac{Wf}{PS3\,\theta^{.62}}$

$F_7 = \frac{\partial TT5/\theta}{\partial \tau g}$ vs $\%\ Ng/\sqrt{\theta}$

$F_8 = \frac{PT5}{PS6}$ vs $\frac{Wg\sqrt{TT5}}{PS6}$

$F_9 = \frac{PS6}{\delta}$ vs $\frac{\%Nr}{\sqrt{\theta}}$ & $\frac{Wt\sqrt{TT6}}{A}$

$$F_{10} = \frac{TS6}{TT6} \text{ vs } \frac{\% Nr}{\sqrt{\theta}} \;\&\; \frac{Wt\sqrt{TT6}}{A\,\delta}$$

$$F_{11} = \frac{\partial \tau\, \theta/\delta}{\partial \dfrac{Wf}{PS3\ \theta^{.62}}} \text{ vs } \% Ng/\sqrt{\theta}$$

$$F_{12} = \frac{PS3}{\delta} \text{ vs } \% Ng/\sqrt{\theta} \;\&\; \frac{PT5}{\delta}$$

$$F_{13} = \frac{PT6}{\delta} \text{ vs } \frac{Wt\sqrt{TT6}}{A\,\delta} \;\&\; \frac{\% Nr}{\sqrt{\theta}}$$

$$F_{14} = \frac{\tau A}{\delta} \text{ vs } \frac{A\ PT6}{\delta} \;\&\; \frac{\% Nr}{\sqrt{\theta}}$$

$$F_{15} = \frac{\tau R}{\delta} \text{ vs } \beta \;\&\; \frac{\% Nr}{\sqrt{\theta}}$$

F_{16} = load signal vs β

F_{17} = % Nr set vs PLA

F_{18} =. Wf/PS3 vs (% Nr - % Nr set)

F_A, F_B, F_C are functions extracted from a computed diverter valve performance map.

F_N = The function of the transient speed coordinator

$$F_N = \frac{Wf/PS3\ Actual}{Wf/PS3\ Normal} \text{ vs } (\% Ng - \% Ng \text{ minimum})$$

D_R = the drop rate of the Ng governor

$$D_R = \frac{\partial\ Wf/PS3}{\partial\ \%\ Ng} \text{ vs } \%\ Ng$$

C_N = A signal from the diverter of the nth engine to the transient speed coordinator. It is used to remove an engine from the transient coordination system in the event that it is diverted.

LS = Load signal from collective pitch to the fuel control in Wf/PS3 units.

MISMATCHED ENGINES

General

It was discovered in the early stages of the XV-9A flight testing that the performance mismatch between engines in a common duct could have serious results. It is therefore necessary to investigate the interaction between engines under the mismatch conditions of unequal compressor bleed, unequal horsepower extraction, and initial mismatch of gas generator speed, Ng.

Mismatched bleed and horsepower are simulated by adjusting the various engine constants, whereas gas generator speed mismatch is accomplished by starting the transients with different values of PLA on the various engines. A mismatched fuel acceleration schedule is used in some of the cases to represent typical engine-to-engine acceleration performance variation.

Two limits were set for the transient performance. The first of these is that the engines should be capable of acceleration without hanging up from an initially mismatched condition of 5 percent ΔNg. This figure is constituted in part from production tolerances and in part from operational tolerances.

Present T64 production engine data indicate that in a random group of engines without trim, it is possible to have a speed mismatch of 3.2 percent ΔNg (this extreme occurs at autorotation). It is also necessary to allow the pilot a tolerance on matching the power lever angles on all engines. A reasonable tolerance is 2° PLA; and since 1° PLA is equivalent to 0.7 percent ΔNg, the resulting speed mismatch is about 5 percent ΔNg.

The second limit, applied from an operational standpoint, is that the time for all engines to reach maximum speed should not be greater than 4.5 seconds.

Results and Discussion

General

Initially the system was run with no coordinating control, to eliminate the effects of mismatch, and with the gas generators at the normal idle power of 3 percent maximum power, which is equivalent to 75 percent Ng. The results of this running are shown in the first group of figures in Table IV. From these results, it can be seen that the system does not meet the limit detailed above, and consequently the study was enlarged to discover a method which would result in the limits being met.

Open A4

Increasing the turbine nozzle area, A4, can be expected to improve ability to accelerate without stall or roll-back, but at the same time it causes a loss of engine performance. An A4 opening to 105 percent of nominal allows acceleration from $1.5 < \% \Delta Ng < 2.0$. Since this offered no significant gain in mismatch tolerance, the effect of modification of the acceleration fuel schedule was examined.

TABLE IV
EFFECT OF OPENING A4 (STANDARD DAY)

		Hang-Up	
		Four Engines	Two Engines (See Fig. 19)
76% Ng Idle 100% Nr	% ΔNg	>1.25	>3.0
	% Wb	> 1.5	>3.25
	Hp ext	> 20	>45
76% Ng Idle 100% Nr A4 = 105% A4 (nominal)		$1.5 < \% \Delta Ng < 2.0$	
As above but with modified Accel. Sch. Wf/P3 included		$2.0 < \% \Delta Ng < 3.0$	

With the intermediate schedule, which has Wf/P3 increased to 120 percent of nominal below 90 percent $Ng/\sqrt{\theta}$ and decreased to 90 percent of nominal Wf/P3 above 100 percent $Ng/\sqrt{\theta}$, the speed split could be increased to 2 percent Ng. This increase is insufficient to meet the requirements; and as the decrease in steady-state performance does not warrant the use of a large A4, this branch of the study was concluded.

Variable Tip Nozzle Area (A8)

It will be remembered from the section on steady-state performance that, by opening the rotor tip nozzle area slightly, the exhaust condition in the common exhaust could be matched. Therefore, it can be appreciated that where mismatched acceleration occurs, the tip nozzle area could be increased in order to match the engines at a critical time.

It had been determined that a tip nozzle area of about 120 percent of nominal would be required to assure engine acceleration from idle with large initial speed splits. Since an area of 120 percent nominal A8 would cause an unacceptable steady-state power loss, the system analysis included the use of a scheduled tip nozzle area, based on the speed of the slowest gas generator. The schedule was chosen such that the tip nozzle area is open to 120 percent nominal A8, with a speed of less than 90 percent Ng and an area of 100 percent nominal A8 above 93 percent Ng, the closure between 90 percent and 93 percent Ng being linear.

From Table V it can be seen that the above schedule permits acceleration from an idle speed split of 3 percent Ng with the intermediate acceleration fuel schedule. However, with an idle speed mismatch of 5 percent Ng, the accelerations were slow.

TABLE V
EFFECT OF VARIABLE TIP NOZZLE AREA

% ΔNg Idle	Accel. Sched.	Day	A8 Schedule Delay (sec)	A8 Schedule Sat (%)	A8 Schedule Lag (sec)	Description of Accel. Hang-Up	Description of Accel. Roll-Back	Description of Accel. Time (sec)	Fig. No.
3	Low	S	No	10	.2	--	Yes	---	20
	Low	S	1	20	.2	No	No	2.5	
	Low	C	1	20	.2	No	No	3.5	
	Low	H	1	20	.2	No	No	2.4	
5	Low	S	No	10	.2	--	Yes	---	21
	Low	S	1	20	.2	No	No	>4.0	
	Low	C	1	20	.2	No	No	4.5	
	Low	H	1	20	.2	No	No	2.8	
3	Int	S	No	No	.02	No	No	4.0	
	Int	S	1	20	.2	No	No	3.0	
	Int	C	No	No	.2	No	No	2.7	
	Int	C	1	20	.2	No	No	3.0	
	Int	H	No	No	.2	No	No	2.5	
	Int	H	1	20	.2	No	No	2.2	
5	Int	S	No	No	.02	No	No	4.7	22
	Int	S	1	20	.2	No	No	3.8	
	Int	C	No	No	.2	No	No	4.5	
	Int	C	1	20	.2	No	No	4.5	
	Int	H	No	No	.2	No	No	3.0	
	Int	H	1	20	.2	No	No	2.8	

Since it was apparently desirable to have the tip nozzle area open transiently at higher speeds, an analysis was made of a system incorporating delayed closing of the tip nozzle area. The assumption is made that the delay can be readily incorporated into a practical A8 control mechanism without substantial complication.

The delay built into the system consists of three parts:

1. A maximum actuation rate of 20 percent A8 per second. This is assumed to be provided by some damping device such as a servo actuator and pilot valve.

2. Actuation is delayed by 1 second after the low-speed engine reaches 90 percent Ng. This delay is present only during acceleration and is assumed to be provided by servo overtravel and slew rate.

3. A 0.2-second actuator lag is included as being incidental to a practical control, although it is neither specifically desired nor very significant to the transient performance.

The above modifications improved the tolerance of the system, but the duration of the accelerations is still thought to be long, particularly under cold (-65°F) conditions.

Another adverse feature of the variable tip nozzle system is that complex mechanical components will be positioned in a very high centrifugal field.

During this part of the analysis, the effect of acceleration fuel schedule, Wf/P3 variation, was tried. One of these schedules was lower than the normal T64 schedule during all the accelerations, whereas the intermediate schedule was the one used previously in determining the effect of opening A4.

In order to demonstrate the effects of the changes in mismatch speed and coordination scheme, various curves have been drawn (see Table V).

High Idle Speed

After completion of the common exhaust system acceleration analysis as described in the preceding paragraphs, it was determined that the idle speed was unnecessarily low. Figure 23 shows the gas generator idle speeds necessary for flat pitch rotor operation. After consultation with the Hughes Tool Company, it was agreed that a flat pitch speed of 70 percent Nr could be used without the need for complications such as a rotor brake. This rotor speed gives a gas generator speed of approximately 87 percent Ng and a power of 10 percent maximum power on a standard day.

The DYNASAR program was run using a constant real speed, Ng = 87 percent, but since this results in a power approaching maximum power on a cold day, this speed must be controlled as a function of compressor inlet temperature.

From the graphs of the transient performance, it can be seen that hang-up occurs when the slow engine lags the remaining engine(s) by approximately 20 percent in the two-engine system and by 10 percent in the four-engine system. The fuel system control cam would therefore be profiled to maintain the difference between idle and maximum speed constant at the value for the standard day.

The accelerations are therefore not significantly different when the real speed of the gas generators is used, and the results given in this section for real speed apply approximately to corrected speed also. When the acceleration coordination is used, the type of speed signal has no effect upon the transient.

Analysis of the acceleration performance of the system was recommended using the high idle speed, and Table VI shows the results of the initial running.

TABLE VI
HIGH IDLE SPEED: NO COORDINATING SCHEME

% ΔNg Idle	Accel. Sched.	Day	Rotor Speed (%)	Description of Accel. Hang-Up	Roll-Back	Time (sec)	Fig. No.
3	T64	S	100	No	No	1.7	23
	Int	S	100	No	No	3.3	
	T64	C	100	No	No	1.7	
	T64	H	100	No	No	1.1	
4	T64	C	100	No	No	2.0	
	T64	H	100	No	No	1.2	
5	T64	S	100	No	No	2.7	
	Int	S	100	Yes	No	>5.0	
	T64	C	100	No	No	3.0	
3	T64	S	70 constant	No	No	2.6	24
	T64	C	70 constant	No	No	2.2	
	T64	H	70 constant	No	No	1.5	
4	T64	S	70 constant	---	Yes	∞	
	T64	C	70 constant	---	Yes	∞	
	T64	H	70 constant	No	No	1.6	
5	T64	H	70 constant	No	No	1.8	

Initially the transients were run with a rotor speed of 100 percent Nr, but for the later runs this was dropped to a constant 70 percent Nr, this being the ground idle speed.

From the results in Table VI, it can be seen that with the lower rotor speed the engines would not accelerate away from a speed mismatch of 4 percent Ng. This is unacceptable, and it became necessary to examine schemes for coordinating the accelerations of the gas generators.

Two schemes were examined, one being a compressor discharge pressure coordinating scheme and the other using gas generator speed. The latter was selected due to the inherent simplicity of such a scheme.

Transient Speed Coordinator

The transient speed coordinator selected is as shown in Figure 16.

The coordinator receives a speed signal from each engine. The minimum (percent NG min) of these signals is selected and is independently subtracted from each of the incoming speed signals to obtain $\Delta\ \%Ng_1, \Delta\ \%Ng_2$, etc. In the DYNASAR program, for each Δ % Ng a functional signal (F_N) is generated and transmitted to the main fuel control of that particular engine. The function F_N is the ratio of the required fuel flow to the engine to that scheduled by the fuel control and is shown in Figure 26. The effect is that the fuel flow Wf/P3 is reduced proportional to F_N. A minimum value is set for F_N of 0.85 in order to prevent engine blowout during throttle chops.

An attempt was made to utilize the Ng coordinator at the low idle speed, but the limit of authority was required to be so low that blowouts could occur during throttle chops, unless the schedule was reset higher for deceleration. With the T64 system, the coordinator schedules a function as shown in Figure 27 such that any schedule slope between 0.3 and 3.0 volts/RPM may be obtained.

The differential speed function output signal operates a compressor discharge pressure (CDP) bleed valve located in the CDP sensing line of each main fuel control. The bleed valve bleeds CDP pressure in the control sensing line in such a manner that the ratio of CDP at the control to the actual engine CDP conforms to Figure 28. The value is such that a mechanical limit prevents this ratio from decreasing below 0.85. In this way, the control will sense a reduced CDP and reduce the fuel flow accordingly.

In order to allow diverted engines to be ignored in the control, signals B and C (Figure 16) prevent the % Ng from the diverted engine from being considered in the selection of percent NG minimum and maintain the value of F_N for this engine at 1.0.

The following requirements will be applied to a typical aircraft system.

a. Transient Coordinator Response

The transient coordinator (not including the CDP bleed valves) shall have a time constant no greater than 0.01 second. Each CDP bleed valve shall have a time constant no greater than 0.06 second.

b. Operating Range

The transient coordinator shall function properly within the speed range of 11,000 to 19,000 RPM and with speed differences up to 7,000 RPM.

c. Power Requirement

The transient coordinator shall operate using an electrical power supply of 28 volts DC per Mil-E-7894. The system with three bleed valves operating shall require no more than 200 watts.

d. System Lockouts

The transient coordinator shall be designed such that each engine has a separate lockout device. The device shall be capable of being operated either manually or automatically upon activation of the diverter mechanism. When an engine is locked out of the transient coordinator, its speed signal shall not be considered in the selection of the master speed signal and its bleed valve shall be fully closed (a CDP ratio of 1.0).

e. Special Requirements

A modification of the existing Main Fuel Control deceleration schedule is required by the transient coordinator. The required deceleration limit is 3.70 ± 0.20 Wf/P3 units.

The results of the analysis using the Ng speed coordinator are shown in Table VII for the four-engine system. In order to simulate production engine variation, the slow engine was assumed to have an acceleration schedule Wf/P3 half a unit below nominal and one of the remaining engines to have an acceleration schedule half a unit above nominal.

The effect of varying the rate of rotor loading was also simulated.

Since the acceleration schedules tried previously seemed to be inferior to the standard T64 schedule, the latter schedule was used for the remainder of the analysis.

It can be seen from Table VII that for very slow rates of rotor loading, no coordinating control is required, but that for rapid loading (rates of 1.0 second), the Ng coordinating control is required. Use of this control allows accelerations from a 7 percent speed mismatch as well as from an 8.5 percent bleed mismatch and 100 horsepower unbalance horsepower extraction.

Two-Engine System

In order to try the assumption that no coordinating scheme would be required for a two-engine system with a high idle speed, transients were run at the most serious condition, rapid rotor loading. The results of these transients are given in Table VIII.

From this table, it can be seen that the two-engine system has no requirement for a coordinating control since accelerations can be accomplished from an idle speed mismatch of up to 7 percent Ng when the high idle speed is used.

TABLE VII
EFFECT OF NG COORDINATOR AT HIGH IDLE SPEED

Mismatch	Day	Rotor Speed	Collective Speed	Description of Accel. Hang-Up	Roll-Back	Time (sec)	Fig. No.
		No Coordination Control					
3% Ng	S	70% Initial	1.0	No	No	3.7	29
	S	70% Initial	2.0	No	No	3.1	
	S	70% Initial	3.0	No	No	2.6	
	C	70% Initial	1.0	No	No	3.6	
	C	70% Initial	2.0	No	No	2.4	
	C	70% Initial	3.0	No	No	3.2	
4% Ng	S	70% Initial		---	Yes	---	
	S	70% Initial	2.0	No	No	4.0	
	S	70% Initial	3.0	No	No	3.2	
	C	70% Initial	1.0	No	No	4.6	
	C	70% Initial	2.0	No	No	2.7	
	C	70% Initial	3.0	No	No	3.3	
5% Ng	S	70% Initial	1.0	---	Yes	---	
	S	70% Initial	2.0	---	Yes	---	
	S	70% Initial	3.0	No	No	3.2	
	C	70% Initial	1.0	---	Yes	---	30
	C	70% Initial	2.0	No	No	3.0	
	C	70% Initial	3.0	No	No	3.6	
6% Ng	S	70% Initial	3.0	No	No	4.3	
	C	70% Initial	3.0	No	No	3.0	
7% Ng	S	70% Initial	3.0	---	Yes	---	
	C	70% Initial	3.0	No	No	3.6	
		With Ng Coordinating Control					
5% Ng	S	70% Initial	1.0	No	No	1.9	
	C	70% Initial	1.0	No	No	2.0	
6% Ng	S	70% Initial	1.0	No	No	1.9	
7% Ng, 8.5% WB, 100 HP ext	S	70% Initial	1.0	No	No	1.9	31
	C	70% Initial	1.0	No	No	2.0	

TABLE VIII
HIGH IDLE SPEED – NO COORDINATING CONTROL

Mismatch	Day	Rotor Speed	Collective Rate	Description of Accel. Hang-Up	Roll-Back	Time (sec)	Fig. No.
5% Ng	S	70% Initial	1.0	No	No	2.0	
	C	70% Initial	1.0	No	No	1.9	
	H	70% Initial	1.0	No	No	1.2	
7% Ng 8.5% Wb 100 HP	S	70% Initial	1.0	No	No	1.2	32
	C	70% Initial	1.0	No	No	2.0	
	H	70% Initial	1.0	No	No	1.3	

Conclusions

As a result of the analysis of the acceleration of mismatched engines, the following conclusions can be made:

1. The high idle speed should be used such that the speed difference between idle and maximum remains constant at the standard day value.

2. In a two-engine system, no coordinating control is necessary.

3. In a four-engine system, a simple Ng speed coordinating system is required.

ROTOR SPEED CONTROL AND TRANSIENT RESPONSE

Results and Discussion

A linear stability study has been conducted on the four-engine system with rotor speed governing. The following power conditions were investigated:

1. Flat pitch at 100 percent Nr (Figure 33)

2. Maximum power at 100 percent Nr (Figure 34).

As was expected, the least stable condition was at flat pitch. However, this condition has good stability (46° phase margin), and if the minimum acceptable phase margin is 30°, which is in accord with good design practice, the system open loop gain can be increased by a factor of 1.68 in order to improve the response.

Several load chops were conducted on the DYNASAR program to determine the rotor transient response, transient speed droop, and steady-state speed droop. The duration of collective pitch motion, in all cases, was 1 second.

Initially, the transients were run without any load compensation. Using the standard droop line (Figure 35), the steady-state droop was 6.6 percent Nr with a transient of 9.6 percent Nr (see Figure 36). These droops are far higher than can be tolerated in the system, and in order to improve the response the system gain should be increased.

The high-gain droop line in Figure 35 increases the rotor governing system open loop gain by a factor of 2.0. The maximum steady-state droop is reduced to 3.5 percent Nr with a peak transient droop of 6.0 percent Nr. However, with the high-gain it should be noted that the persistent oscillations indicate that the system has an equivalent open loop phase margin of approximately 18°, which is unacceptable.

An open loop phase margin of 30°, by comparison, would result in a steady-state droop of approximately 5.5 percent Nr and a transient droop of approximately 8.4 percent Nr.

By comparison with existing rotor governing requirements, the transient performance without load compensation is not acceptable.

For a system with load signal compensation in the form, currently in use, of a feedback from the collective pitch lever, the steady-state droop can be reduced to zero under nominal ambient conditions by proper design of the compensation schedule. Figure 37 shows the results of several collective pitch transients using load signal compensation with the standard droop line. In all cases the overshoot was less than ± 1.0 percent Nr.

The curves in Figure 37 are as follows:

A = 8° Collective to Maximum Collective
B = 6° Collective to Maximum Collective
C = 4° Collective to Maximum Collective
D = 2° Collective to Maximum Collective
E = Flat Pitch to Maximum Collective
F = Maximum Collective to Flat Pitch

General

The rotor speed governing system requires that the Nf drive pad on each main fuel control be driven at a speed proportional to actual rotor speed. The Nf drive pad shall be driven at a maximum governing speed of 3860 RPM and a minimum governing speed of 3345 RPM in a clockwise direction when looking into the drive pad on the main fuel control.

Power Requirements

The power required to drive the Nf drive pad shall not exceed 0.4 horsepower. The torque required shall not exceed 4.0 pound-inches.

Response Rate

The transfer function of the rotor speed drive mechanism shall not exceed 0.2 second.

Special Requirements

The remainder of the rotor speed governing system shall be identical to the existing free turbine speed control in the T64 main fuel control. The ranges of adjustability of the governor gain and of the system time constant listed in the main fuel control specification are adequate for this rotor speed governing system.

Load Compensation

The system requires that the load signal shaft on each main fuel control be positioned as a function of desired power setting (collective pitch). The load signal shaft provided on the rotor speed control should be positioned at 0° for zero load signal and 90° clockwise looking into the control for maximum load signal. The required schedule of load signal shaft position versus percent of maximum load signal is essentially linear.

Conclusions

The prime conclusion which can be drawn from this section is that load signal compensation is required for the transient response of the system to be acceptable. The response of the system without load signal compensation is not acceptable when the stability margin is acceptable.

ROTOR OVERSPEED PROTECTION

General

Rotor overspeed protection requires that a signal be supplied to each main fuel control as an indication of rotor overspeed. An applied voltage shall cause a decrease in equivalent power lever setting. The solenoid shall limit the equivalent power lever setting only when it calls for a setting lower than called for by either the power lever or the rotor speed governor.

Voltage Characteristics

The electrical signal shall be 28 volts with characteristics per Mil-E-7894.

Range of Operation

The rotor overspeed device shall be capable of resetting the equivalent power lever angle to a nominal value which shall be externally adjustable from 33° to 55°.

Power Required

The input signal power required to operate the rotor overspeed device shall be a maximum of 50 watts for each engine.

Response Rate

The maximum delay time from the time the signal is applied to the time the fuel flow is decreasing at the rate of 7,500 pounds per hour per sec shall be 100 milliseconds.

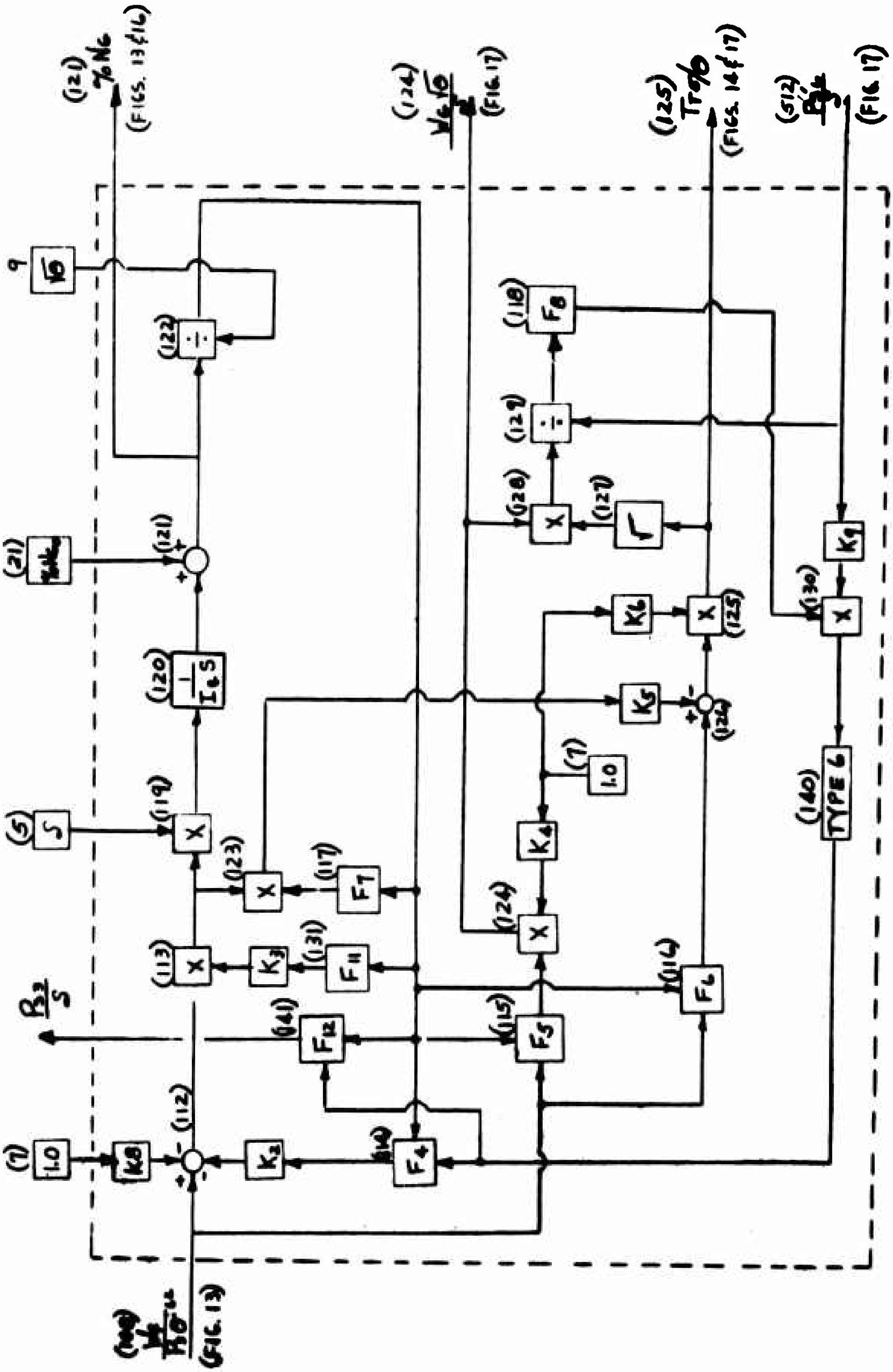


Figure 12. Engine Block Diagram

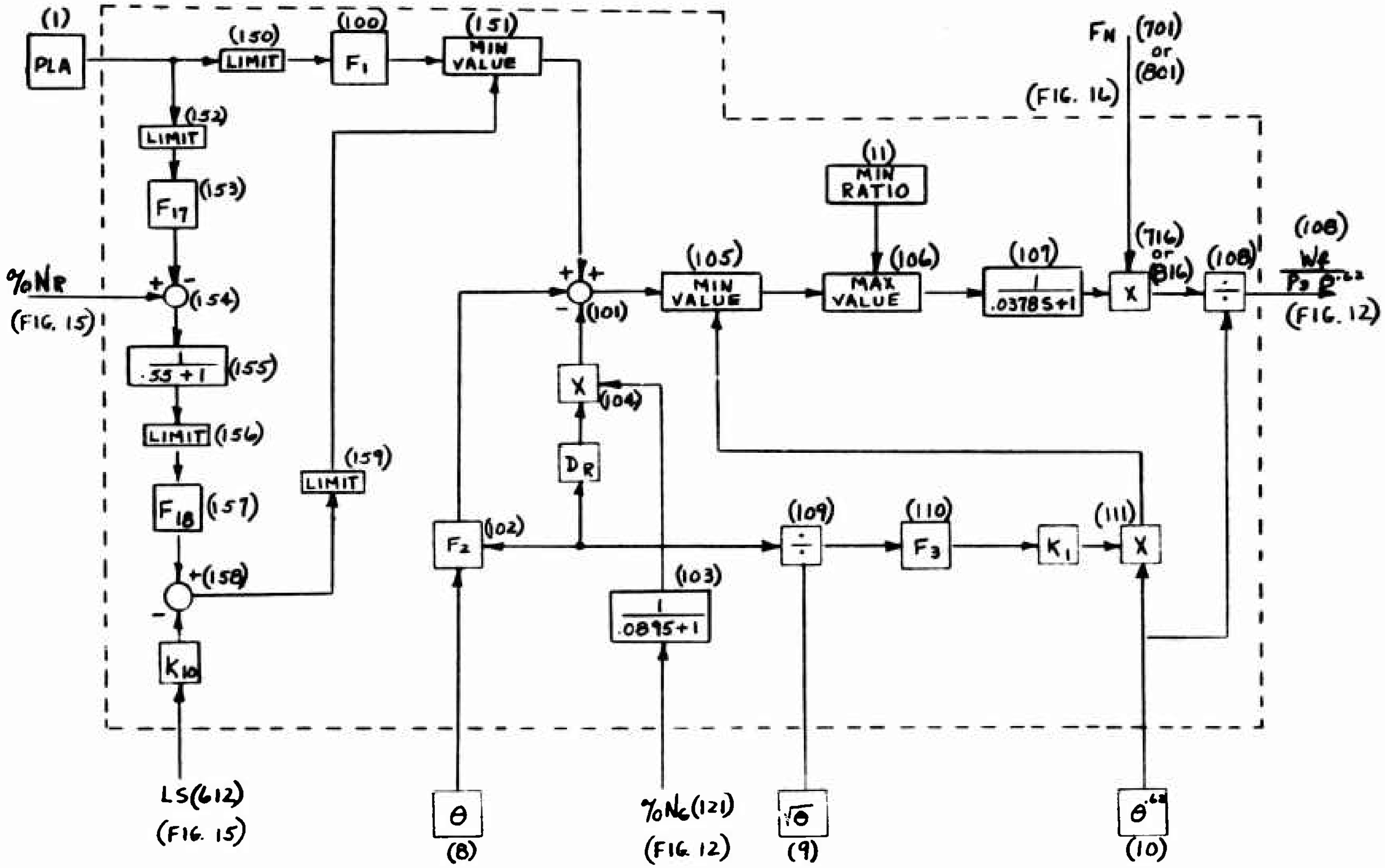


Figure 13. Fuel Control Block Diagram

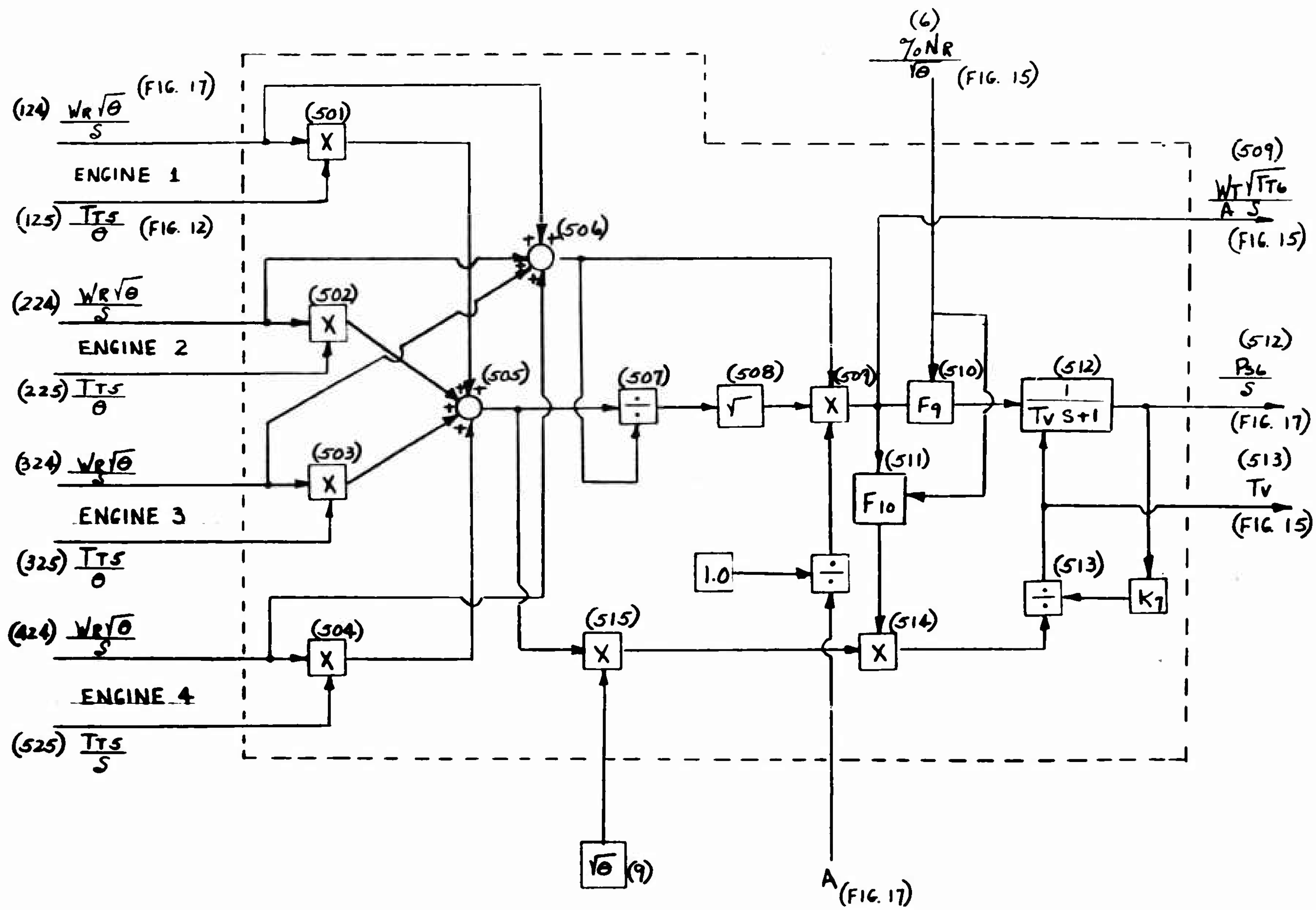


Figure 14. Aircraft Ducting Block Diagram

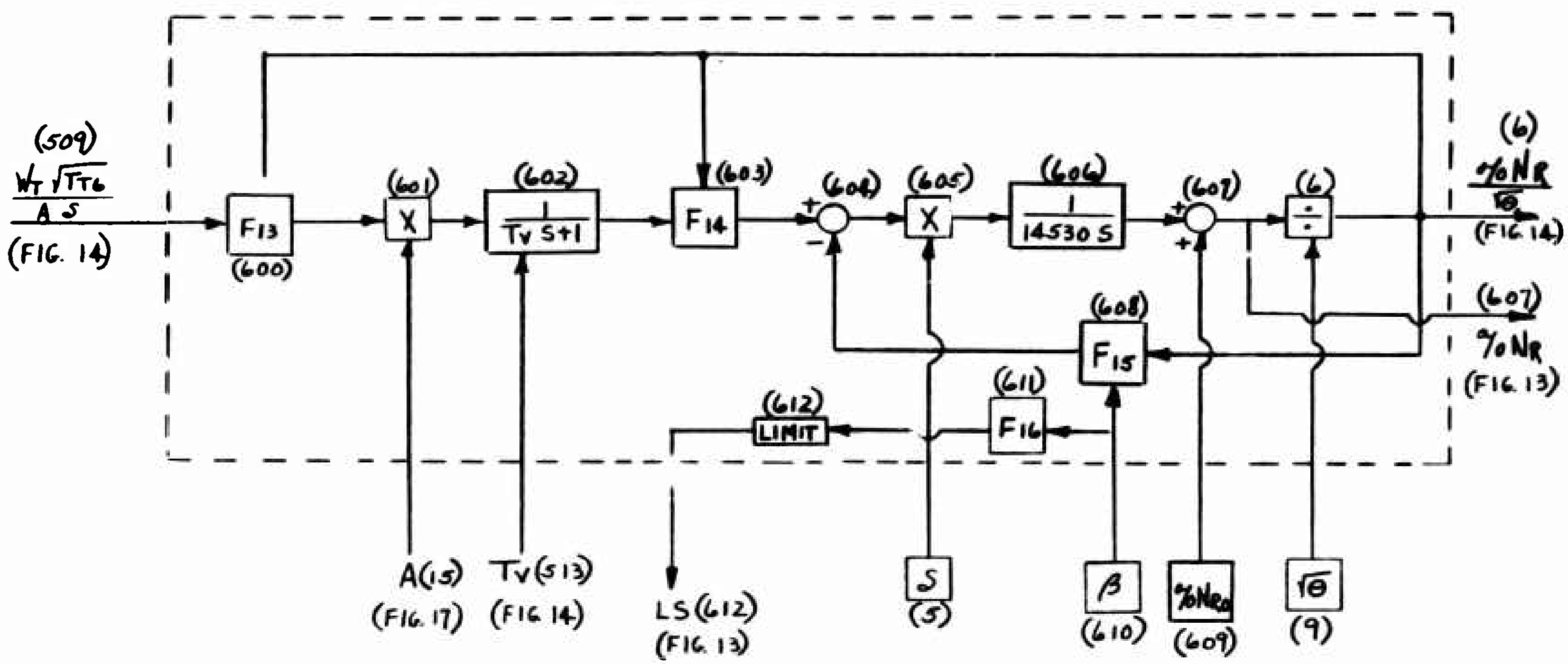


Figure 15. Rotor Block Diagram

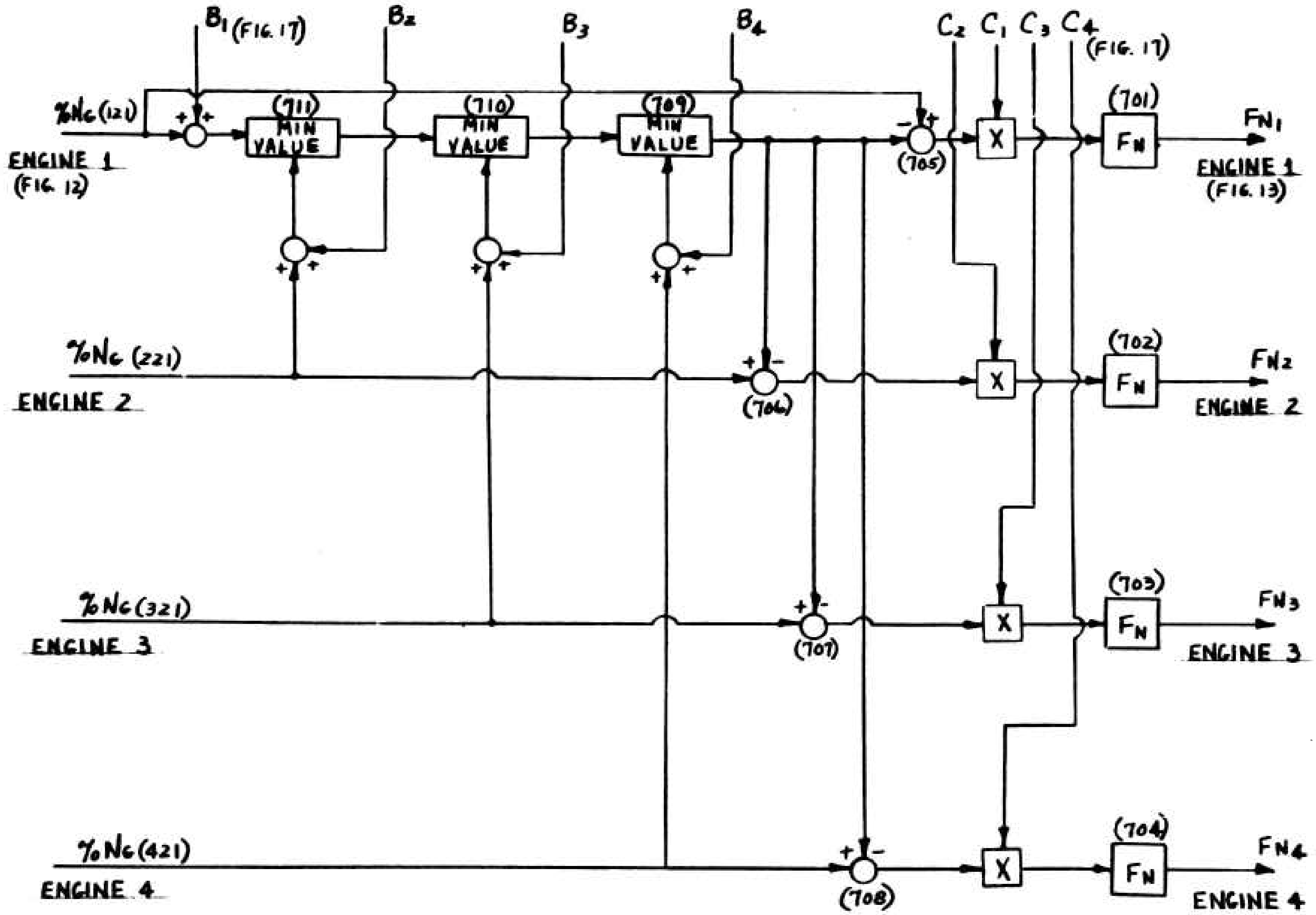


Figure 16. Transient Coordinator Block Diagram

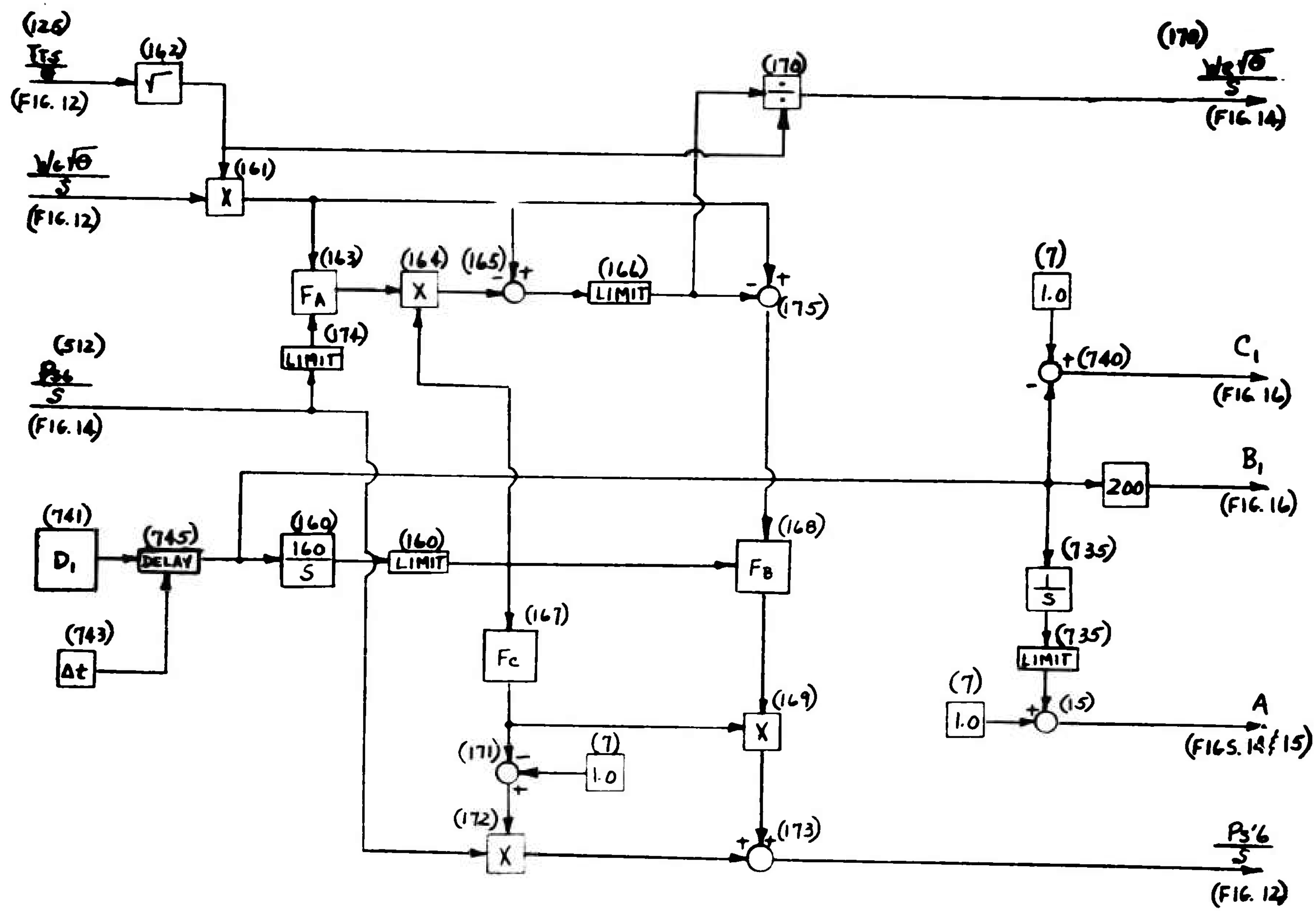


Figure 17. Diverter Block Diagram

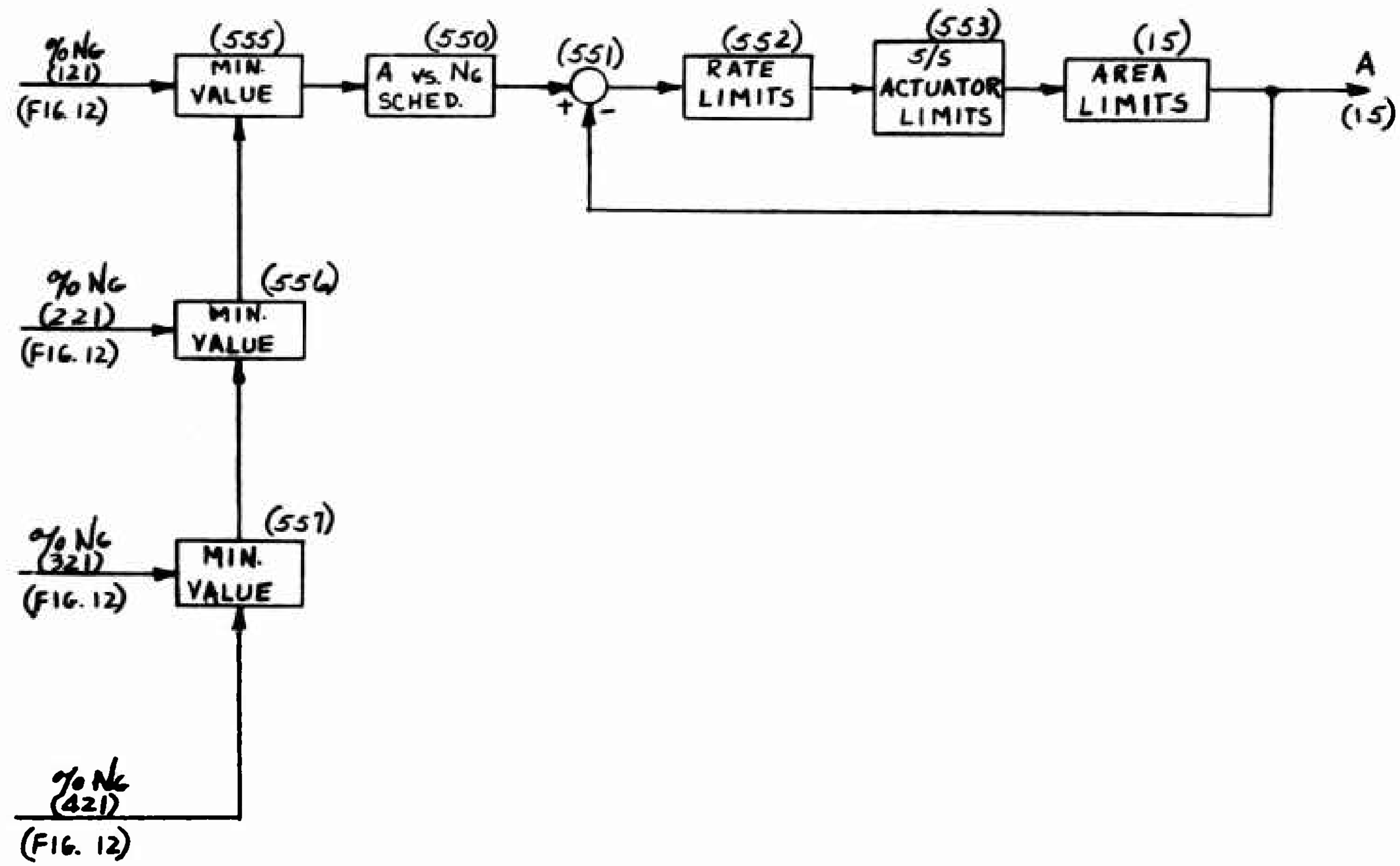
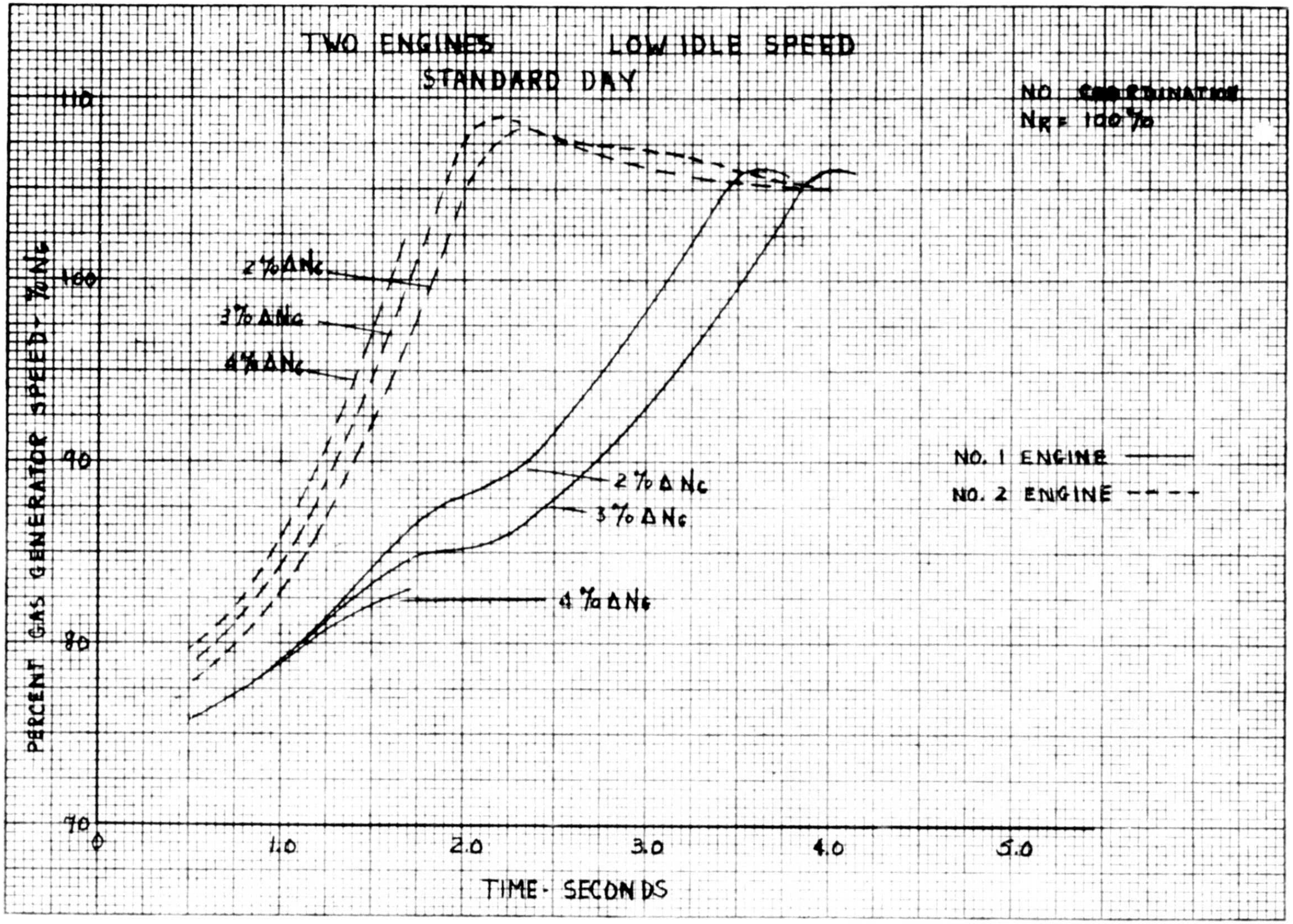


Figure 18. Variable Tip Nozzle Block Diagram



Figu.e 19. Acceleration Response. Two Engines; Low Idle Speed; No Coordination; Nr = 100%: % Ng vs Time

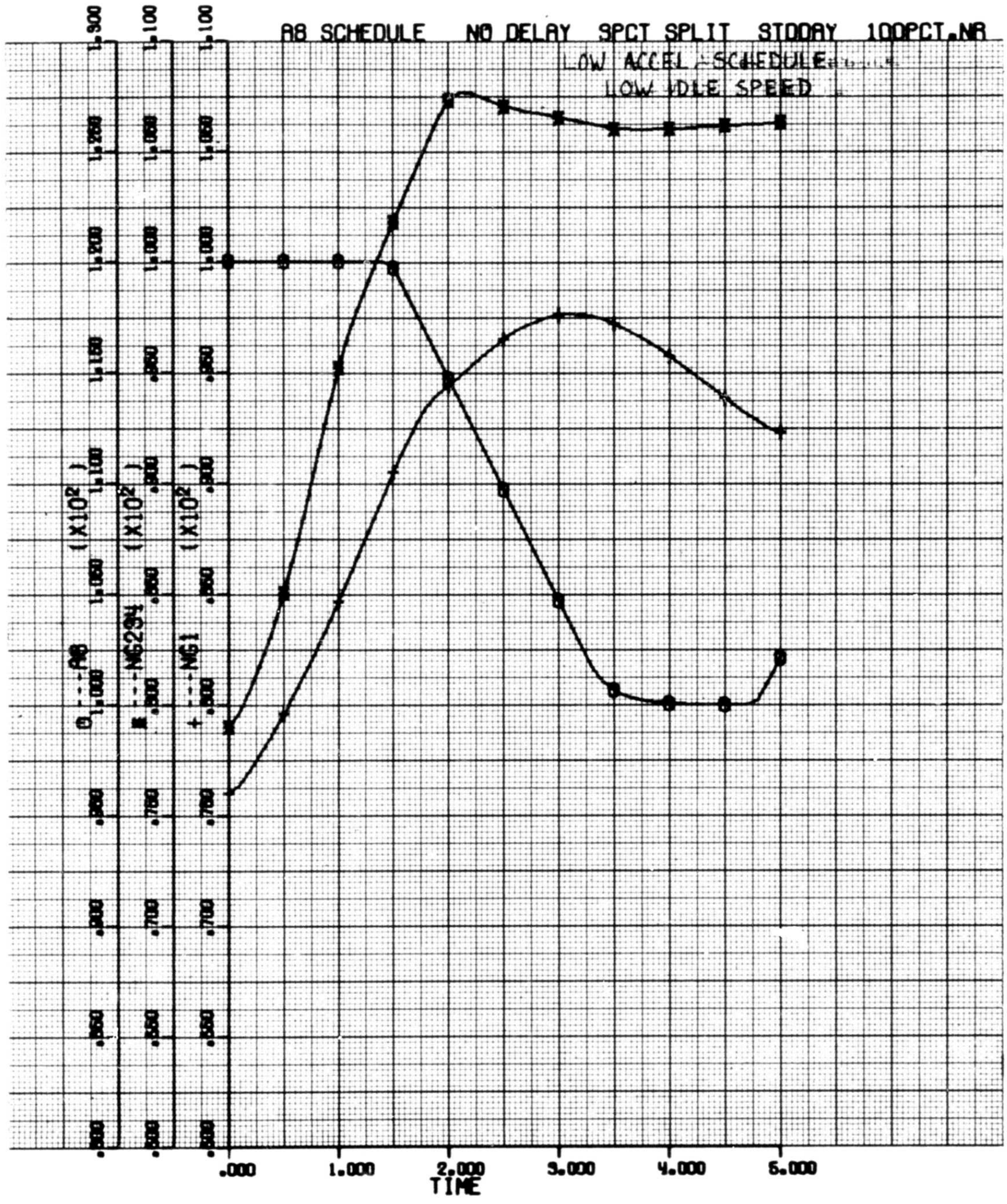


Figure 20. Acceleration Response. Four Engines; A8 Schedule with No Delay; Low Idle Speed; Low Accel. Schedule 3% Δ Ng

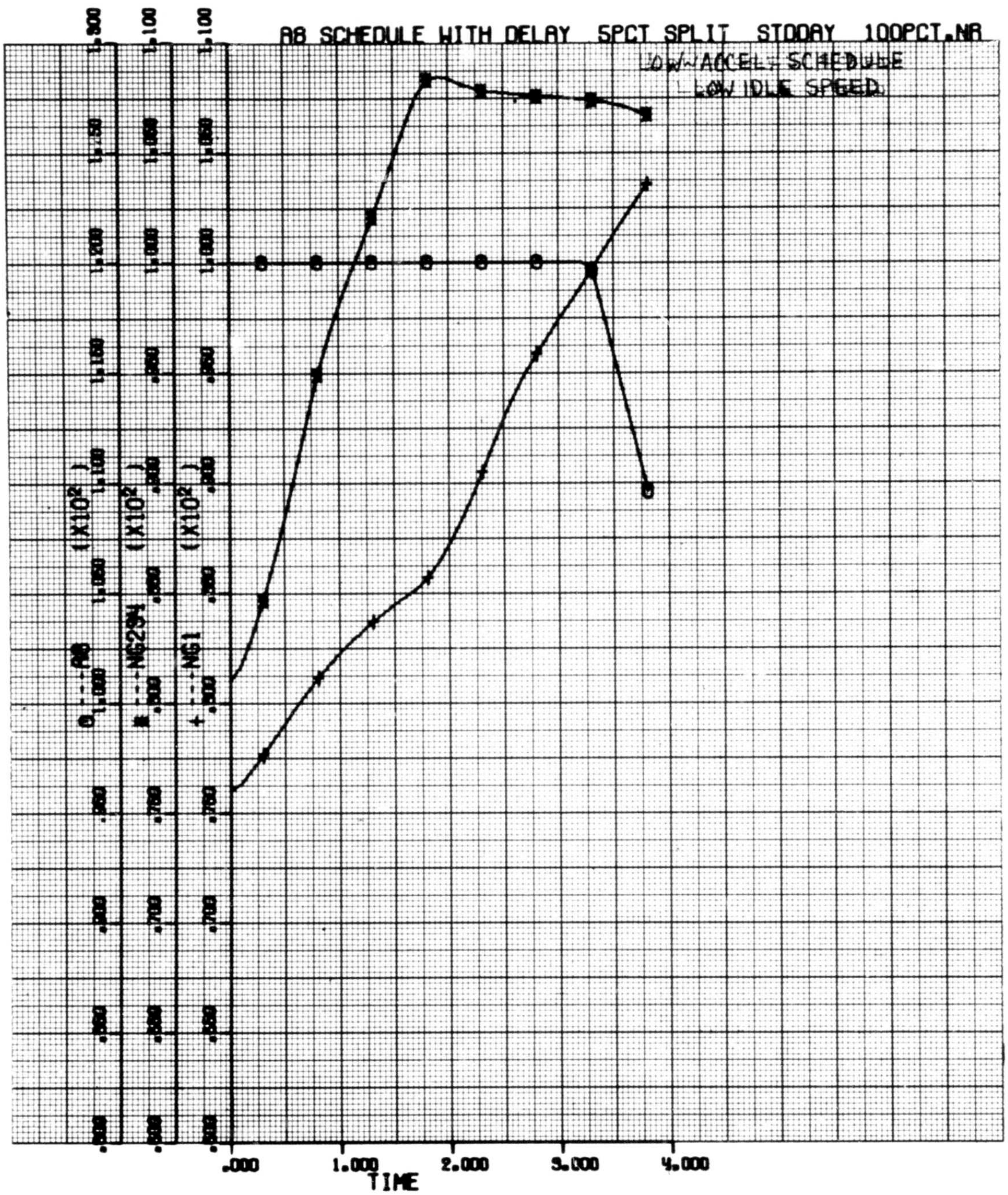


Figure 21. Acceleration Response. Four Engines; A8 Schedule with Delay; Low Idle Speed; Low Accel. Schedule 5% ΔNg; Nr = 100%: % Ng vs Time

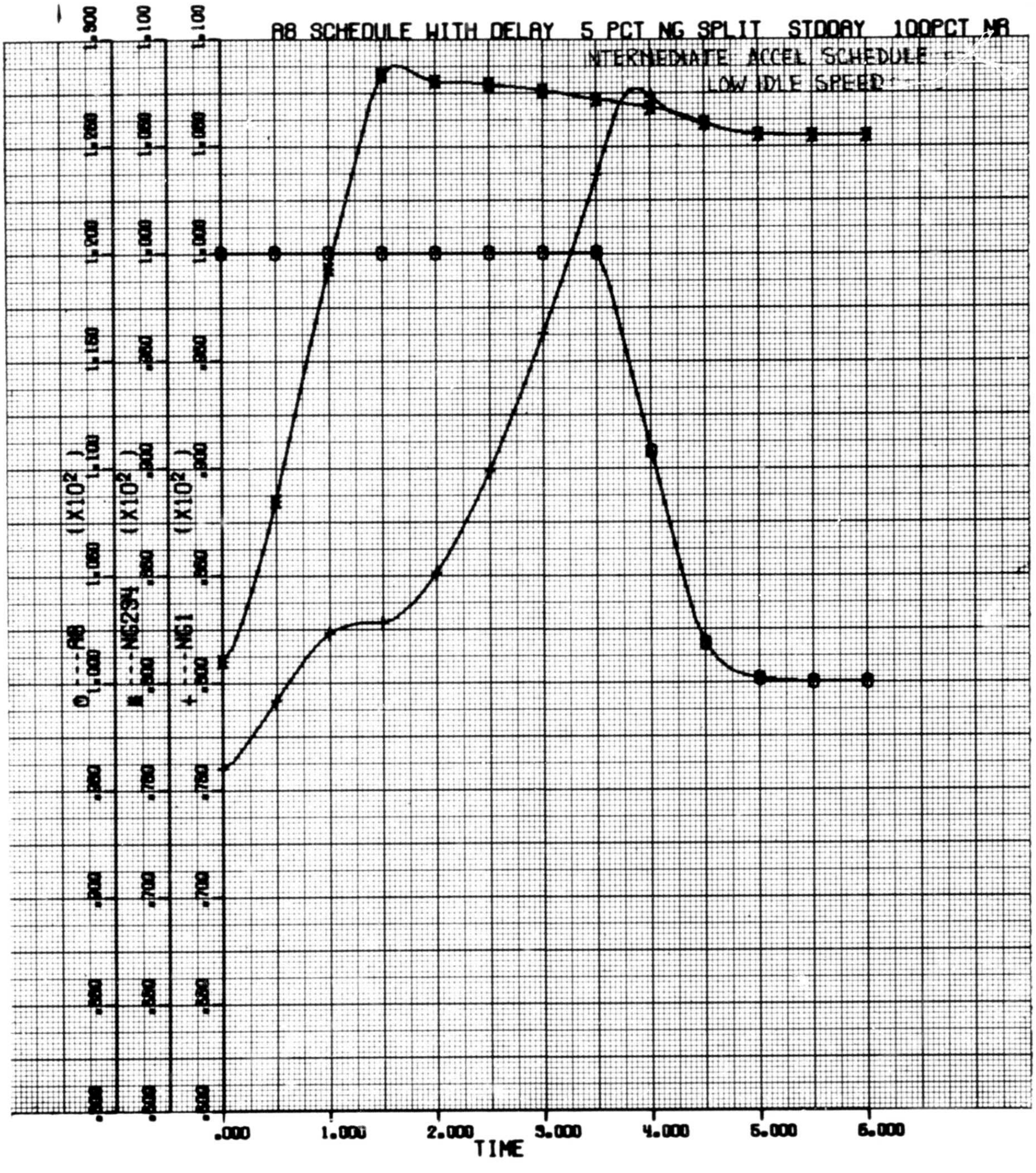


Figure 22. Acceleration Response. Four Engines; A8 Schedule with Delay; Low Idle Speed; Intermediate Accel. Schedule 5% Δ Ng; Nr = 100%: % Ng vs Time

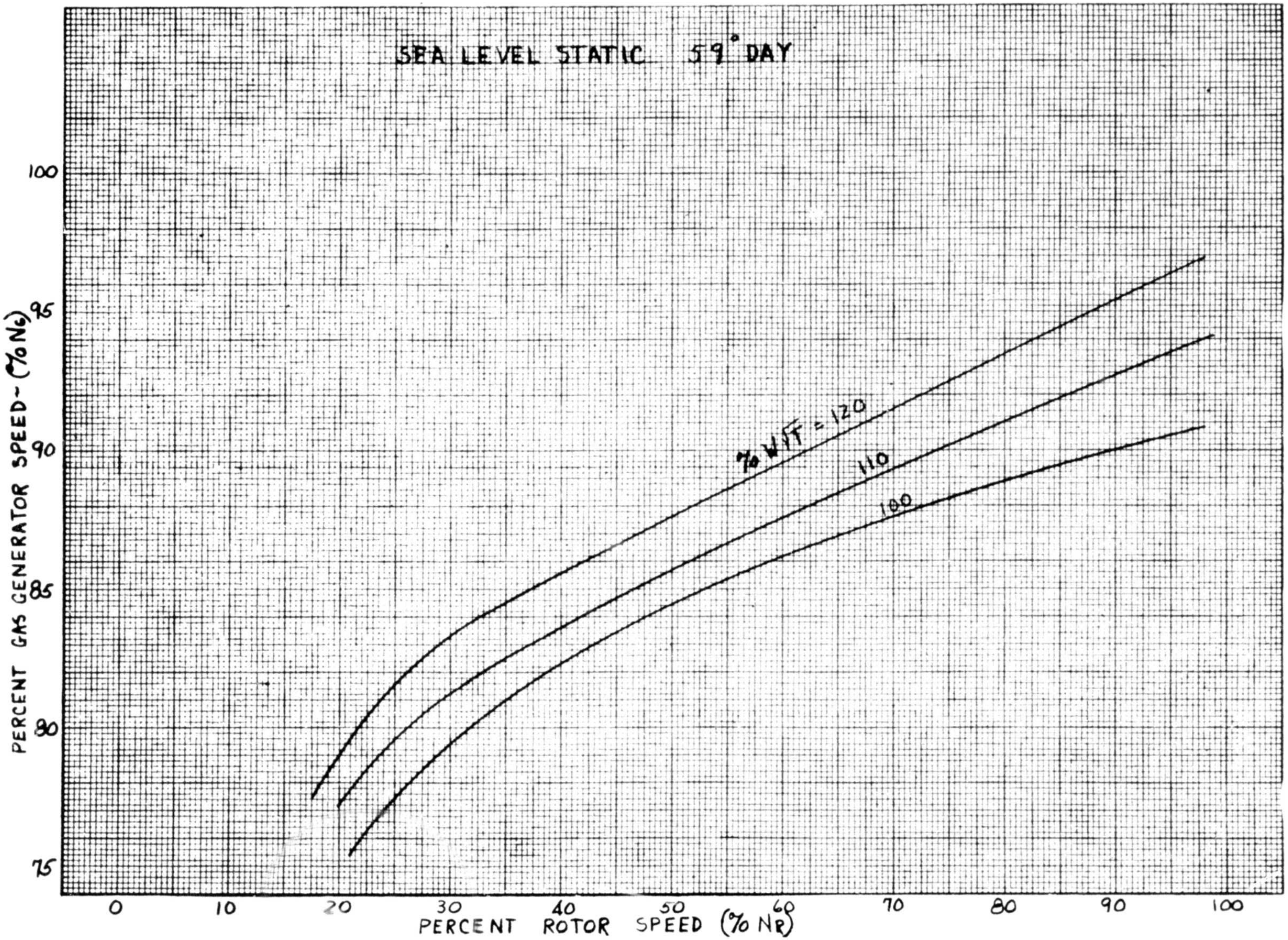


Figure 23. Variation in Ng to Provide Flat Pitch Rotor Power

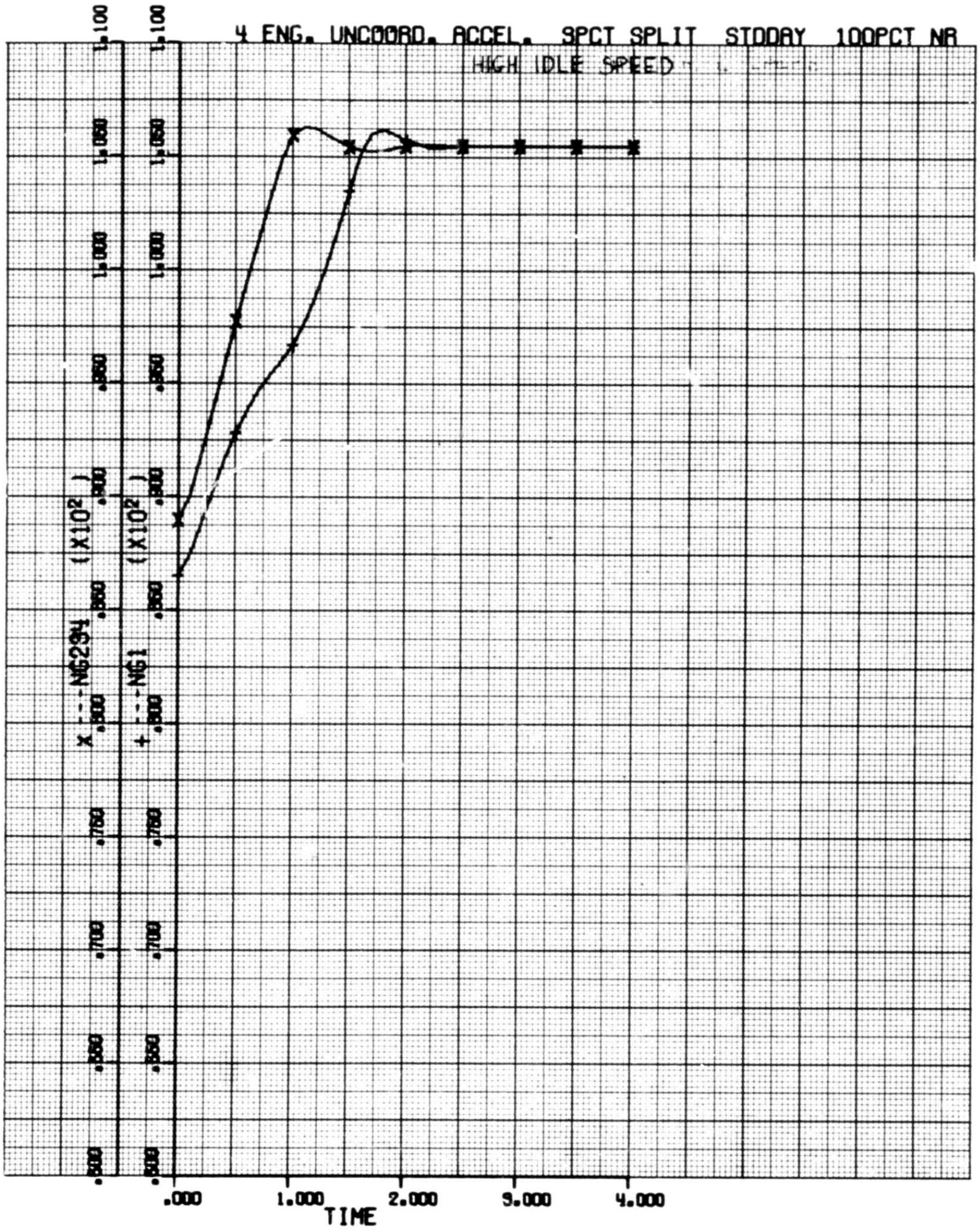


Figure 24. Acceleration Response. Four Engines; Uncoordinated; High Idle Speed; 3% ΔNg; Nr = 100% % Ng vs Time

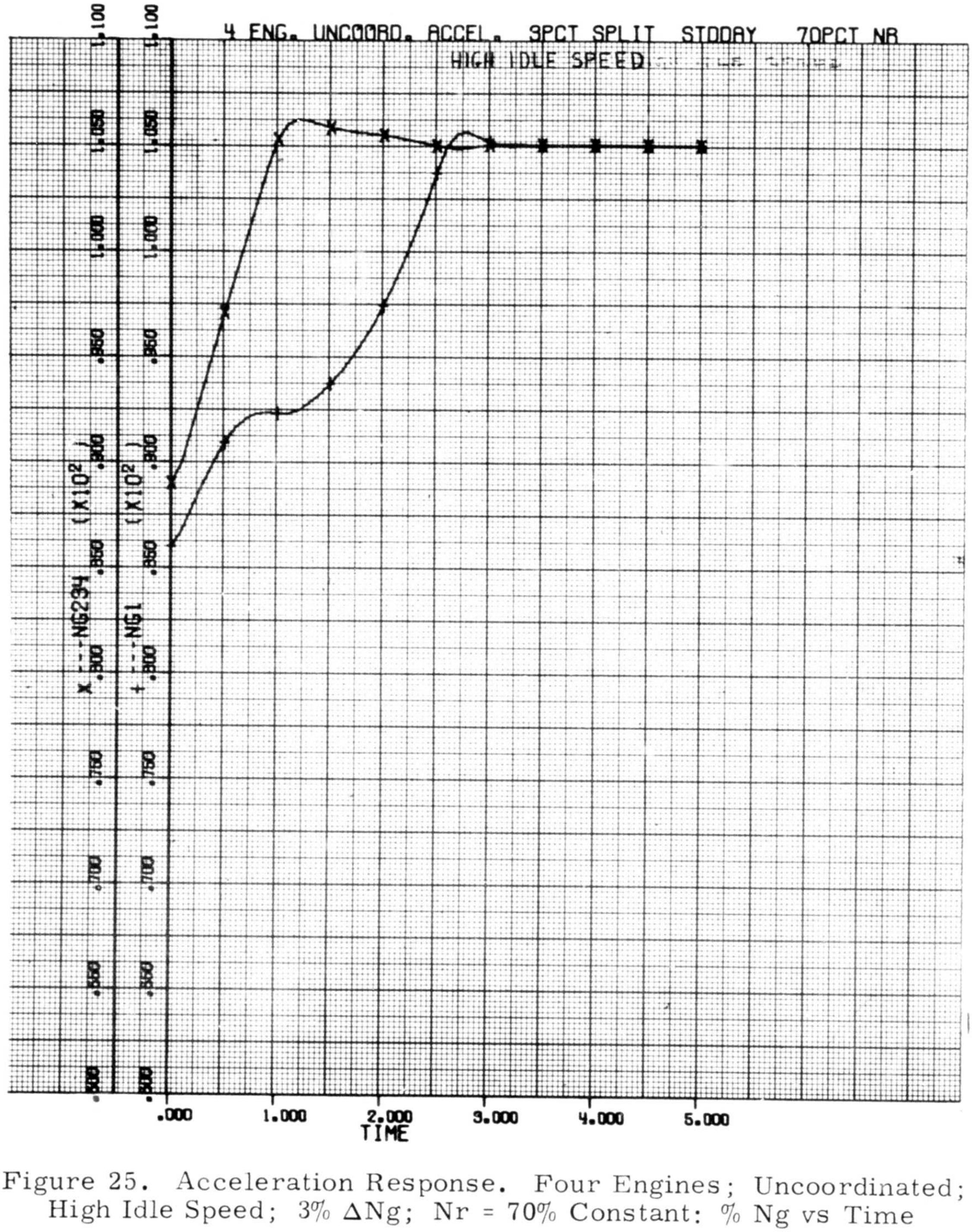


Figure 25. Acceleration Response. Four Engines; Uncoordinated; High Idle Speed; 3% ΔNg; Nr = 70% Constant: % Ng vs Time

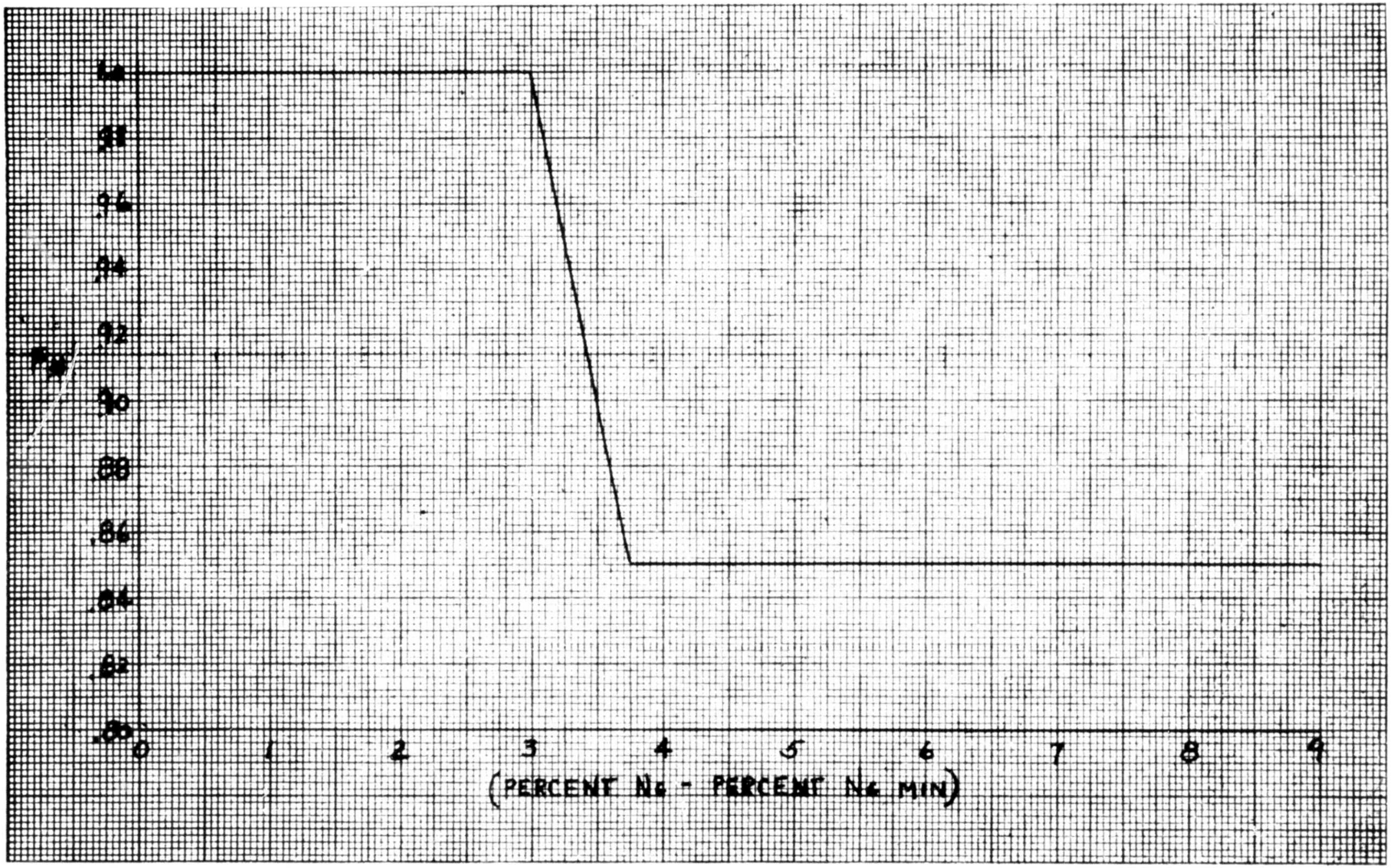


Figure 26. Transient Speed Coordinator Output Function

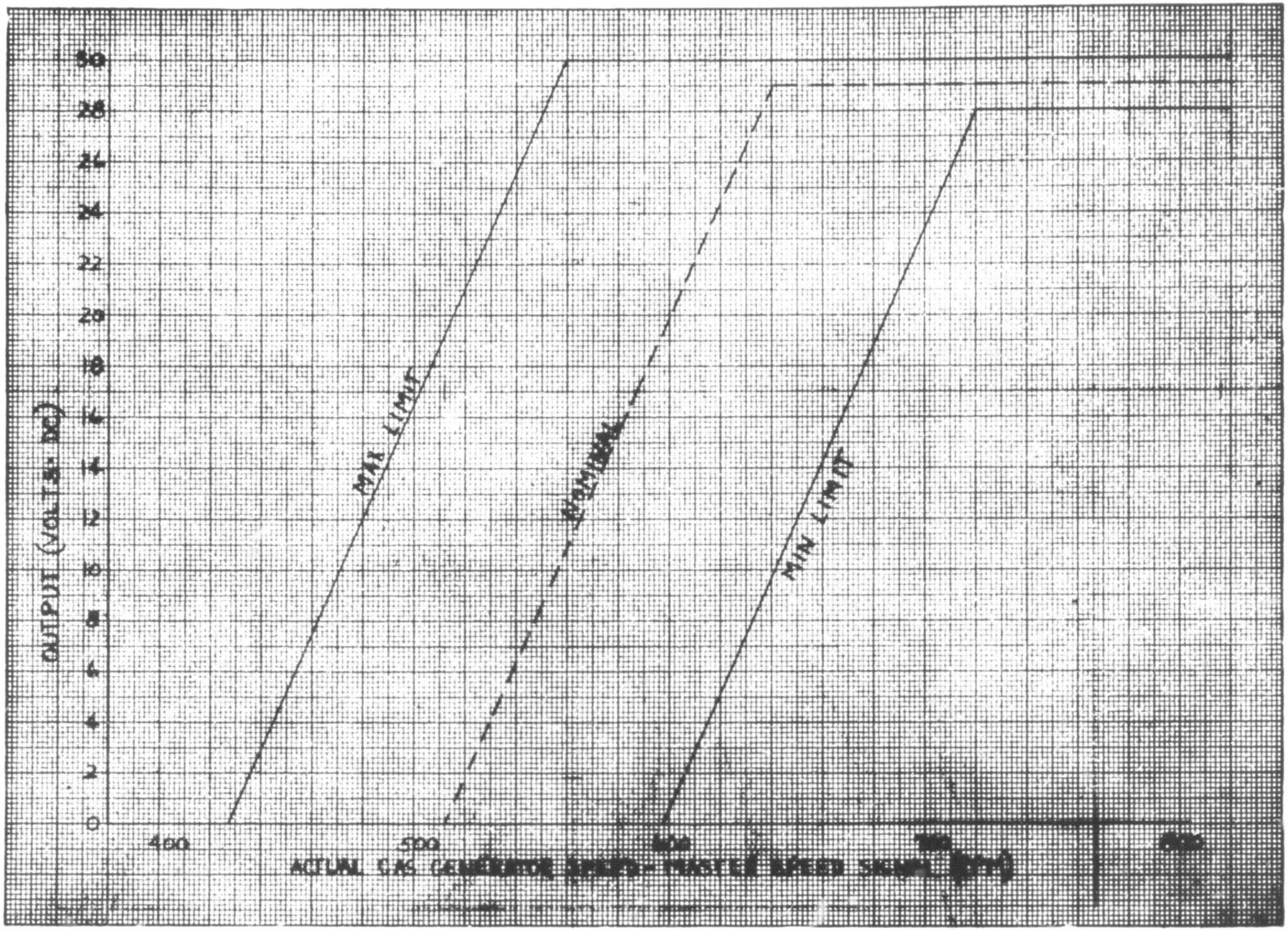


Figure 27. Transient Speed Coordinator Function

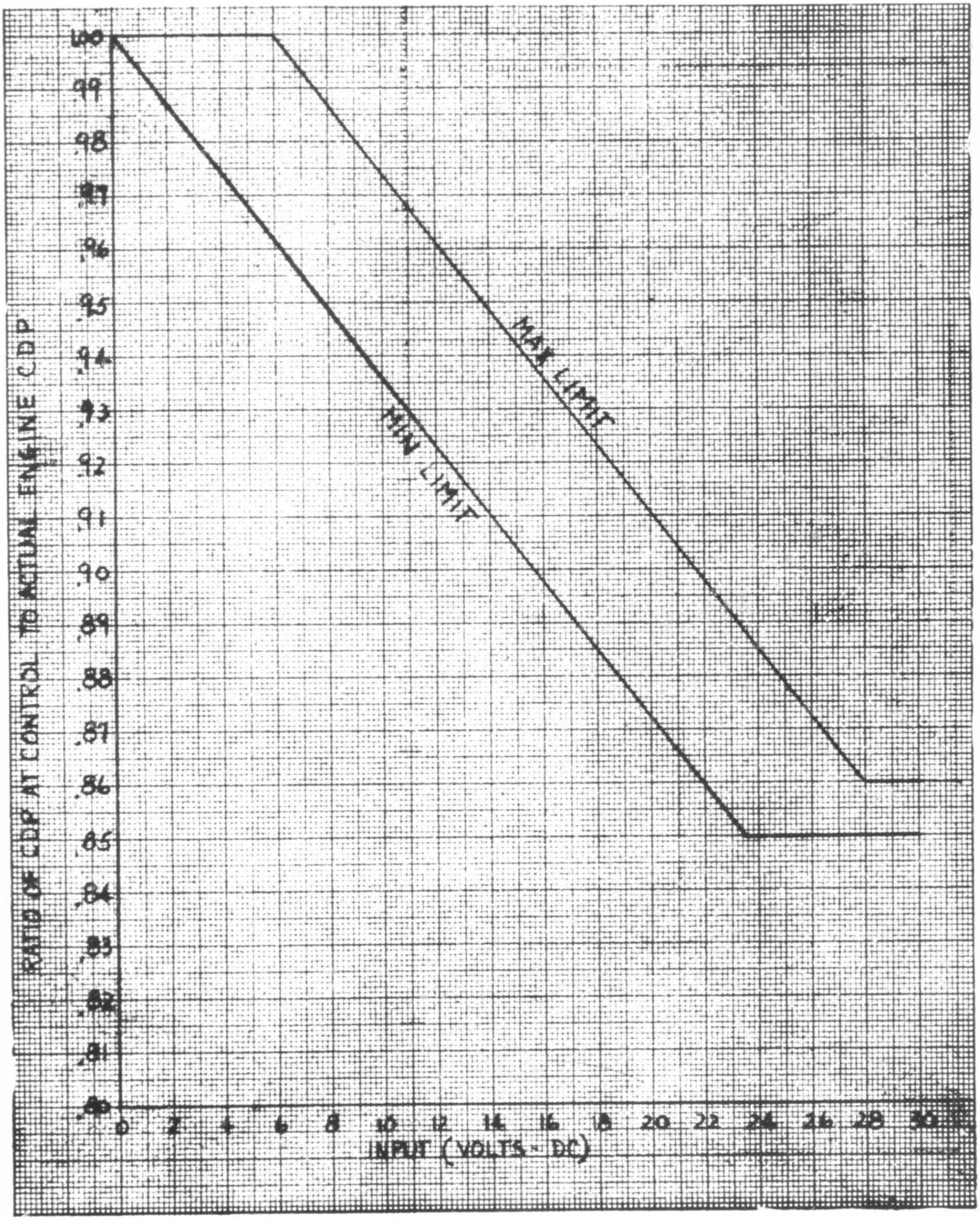


Figure 28. CDP Bleed Valve Function

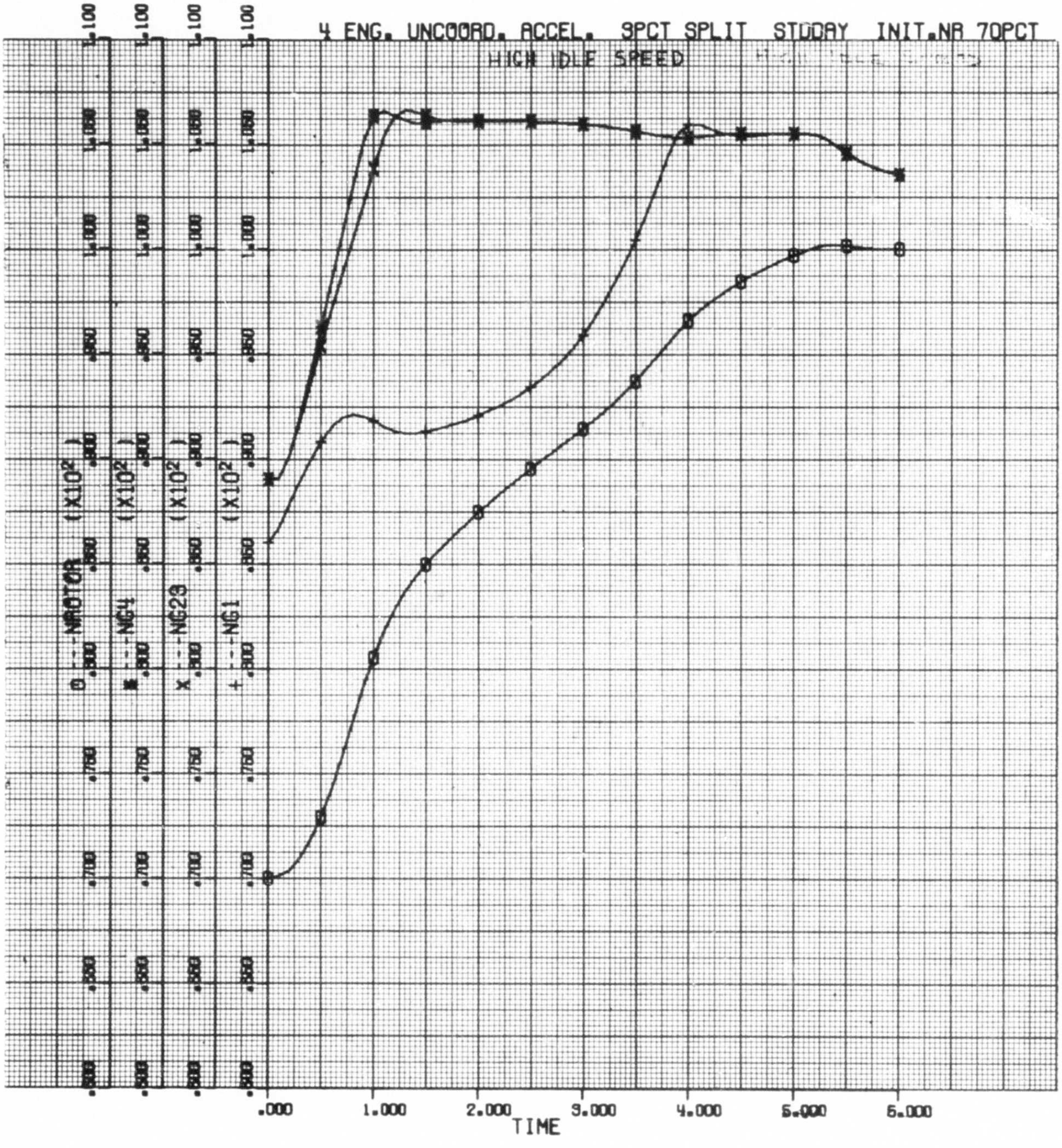


Figure 29. Acceleration Response. Four Engines; Uncoordinated; High Idle Speed; 3% Δ Ng; Nr = 70% Constant: % Ng vs Time

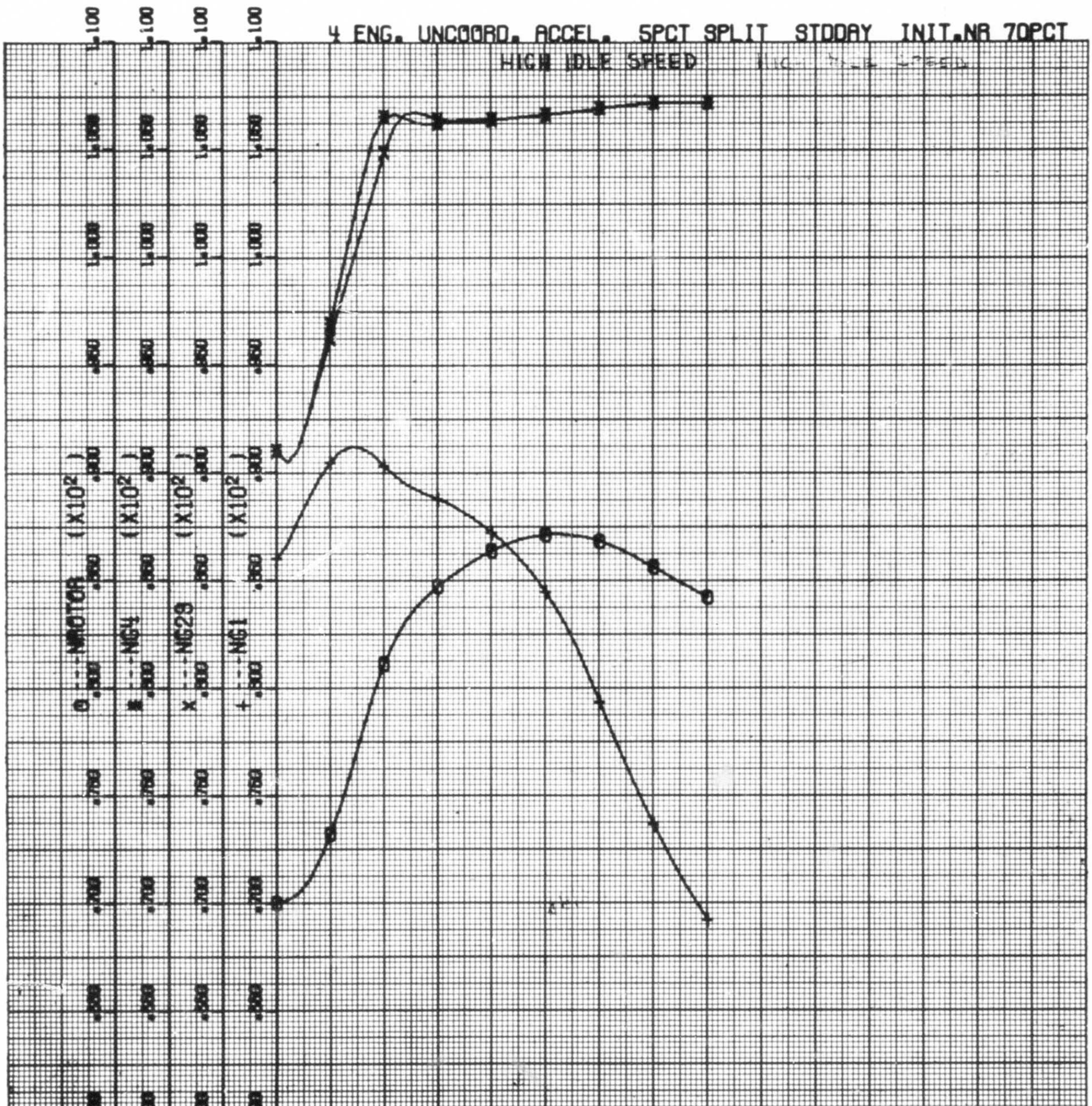


Figure 30. Acceleration Response. Four Engines; Uncoordinated; High Idle Speed; 7% ΔNg; Nr = 70% Initial: % Ng vs Time

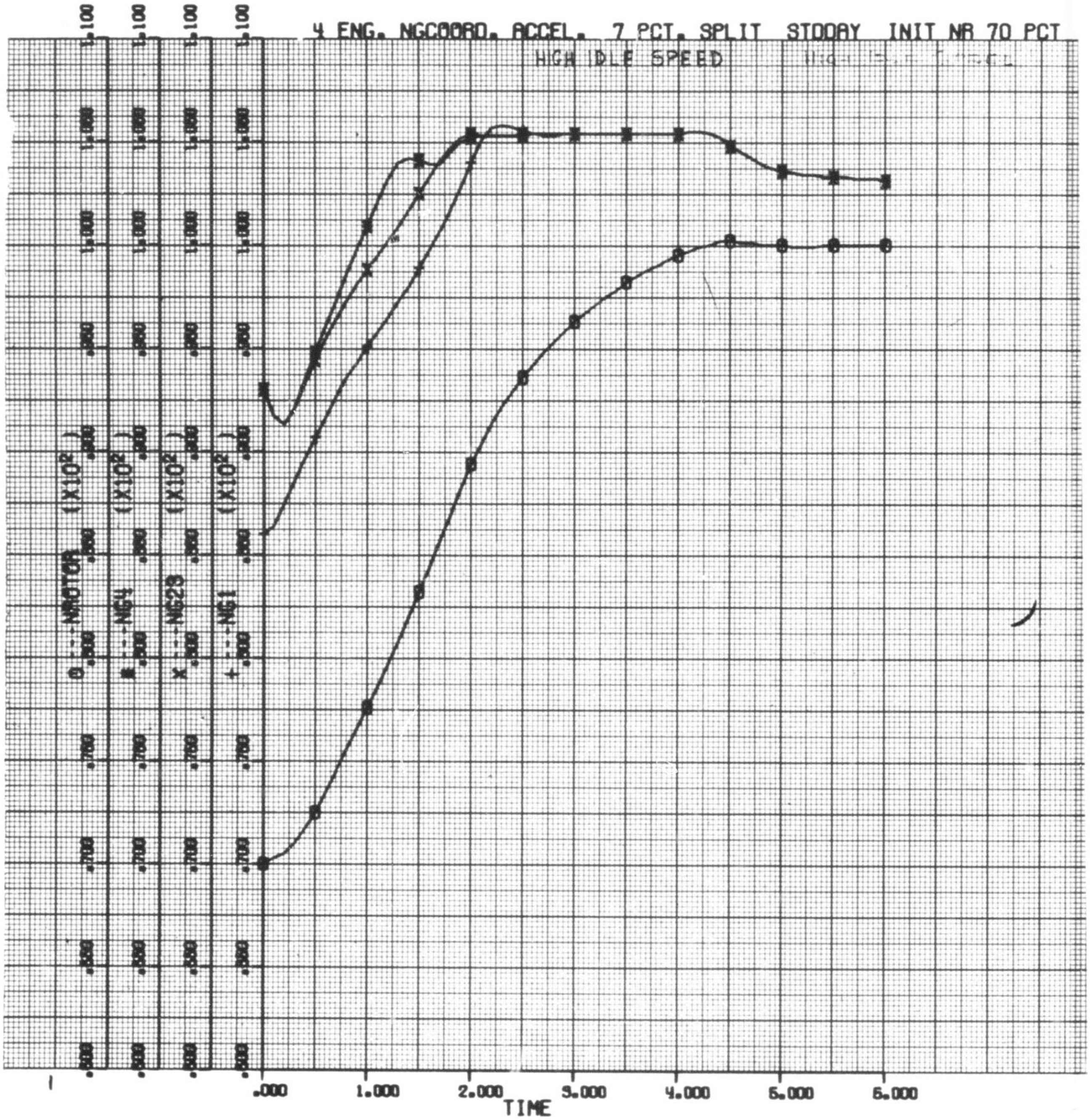


Figure 31. Acceleration Response; Four Engines; Ng Coordination; High Idle Speed; 7% Δ Ng; Nr = 70% Initial: % Ng vs Time

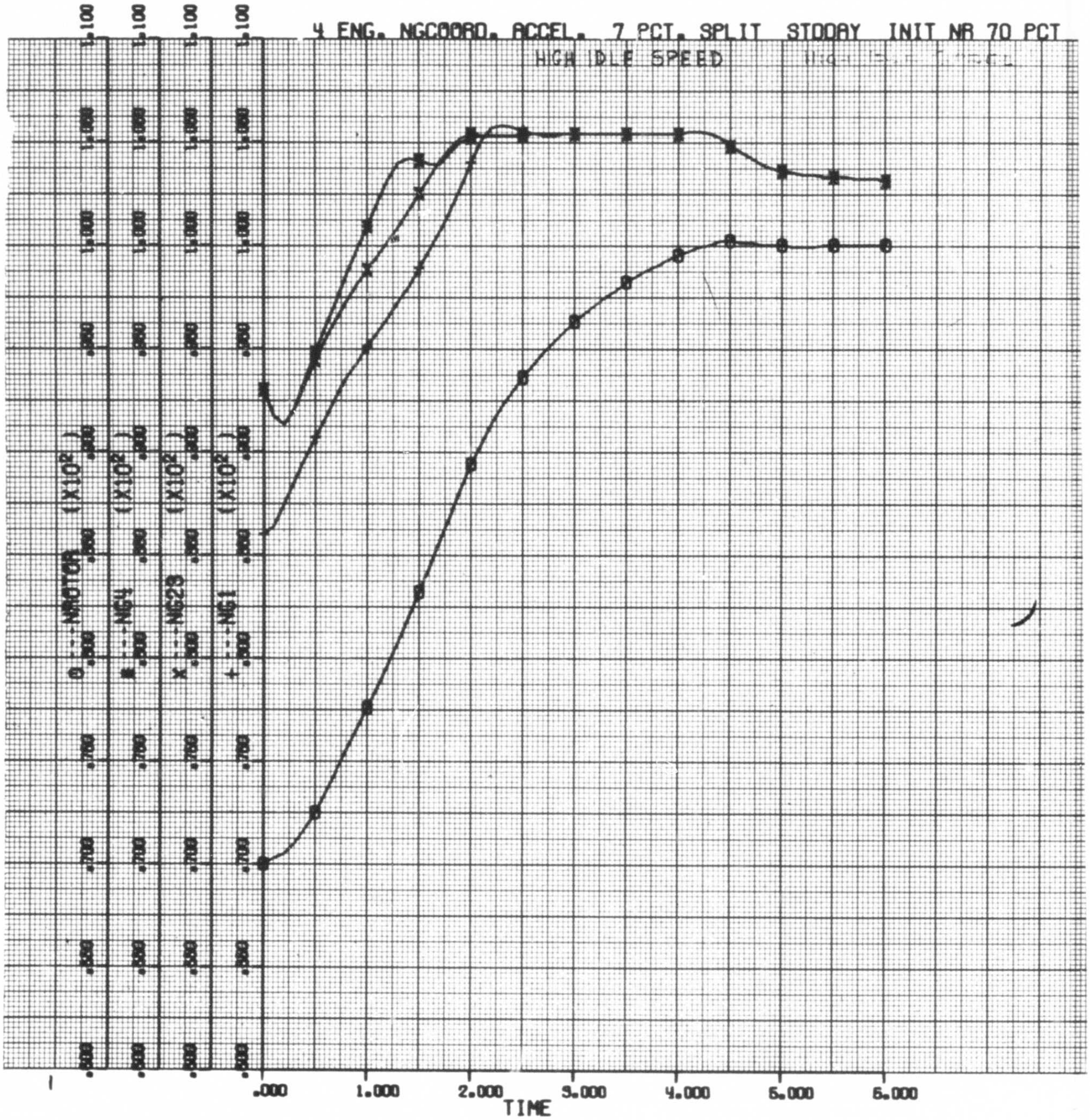


Figure 31. Acceleration Response; Four Engines; Ng Coordination; High Idle Speed; 7% Δ Ng; Nr = 70% Initial: % Ng vs Time

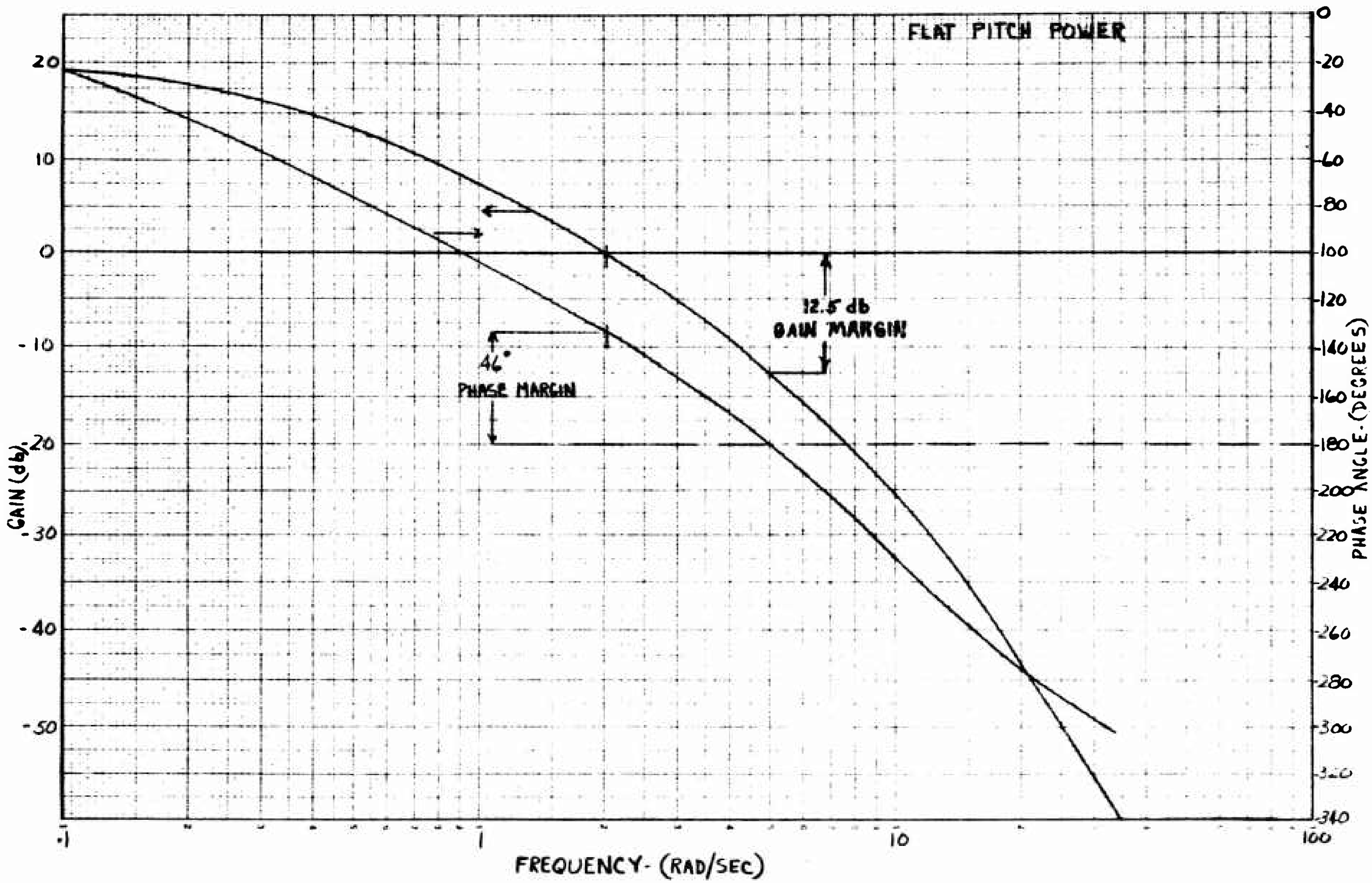


Figure 33. Rotor Governing Open Loop Transfer Function Flat Pitch Power

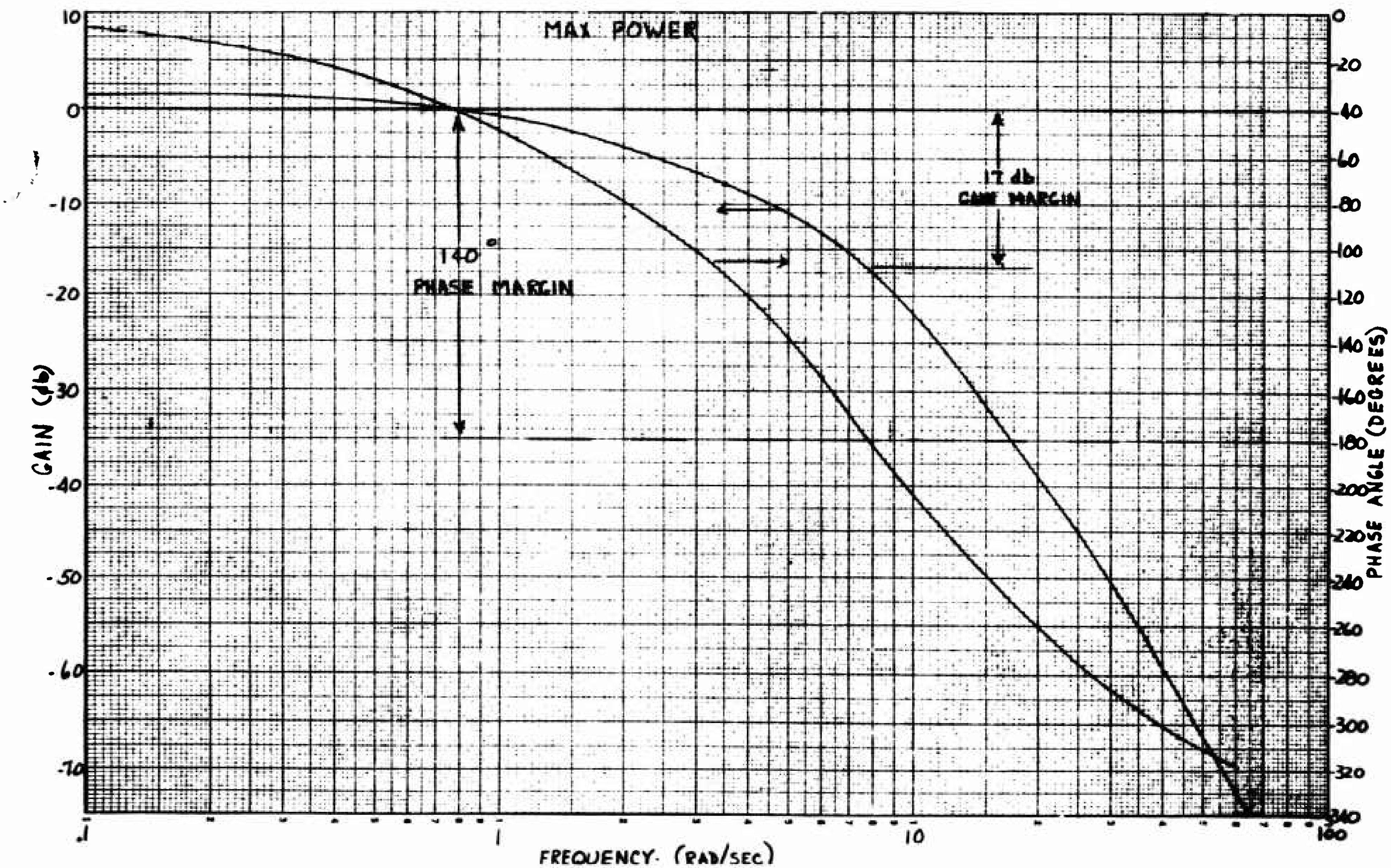


Figure 34. Rotor Governing Open Loop Transfer Function Maximum Power

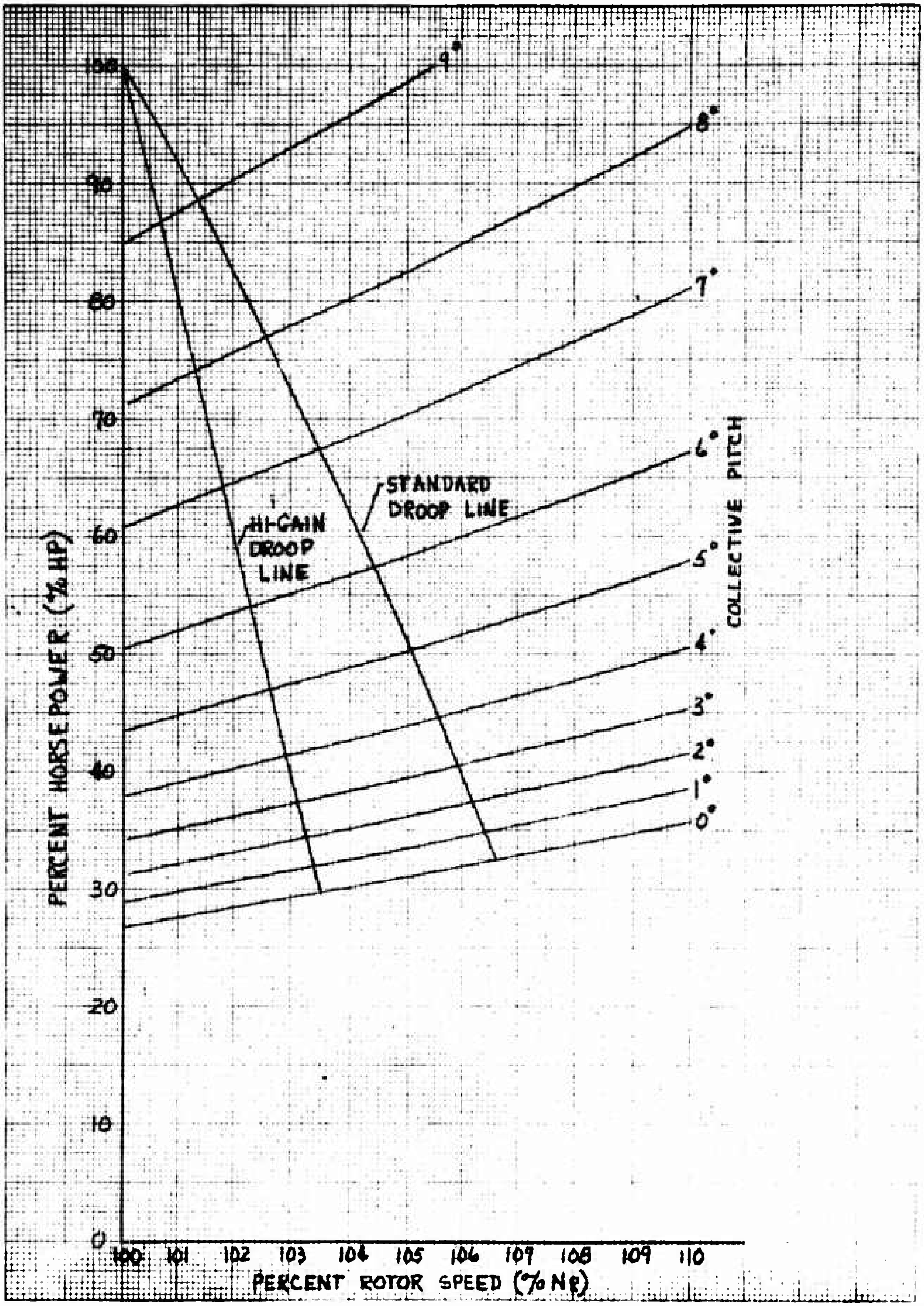


Figure 35. Rotor Steady-State Droop

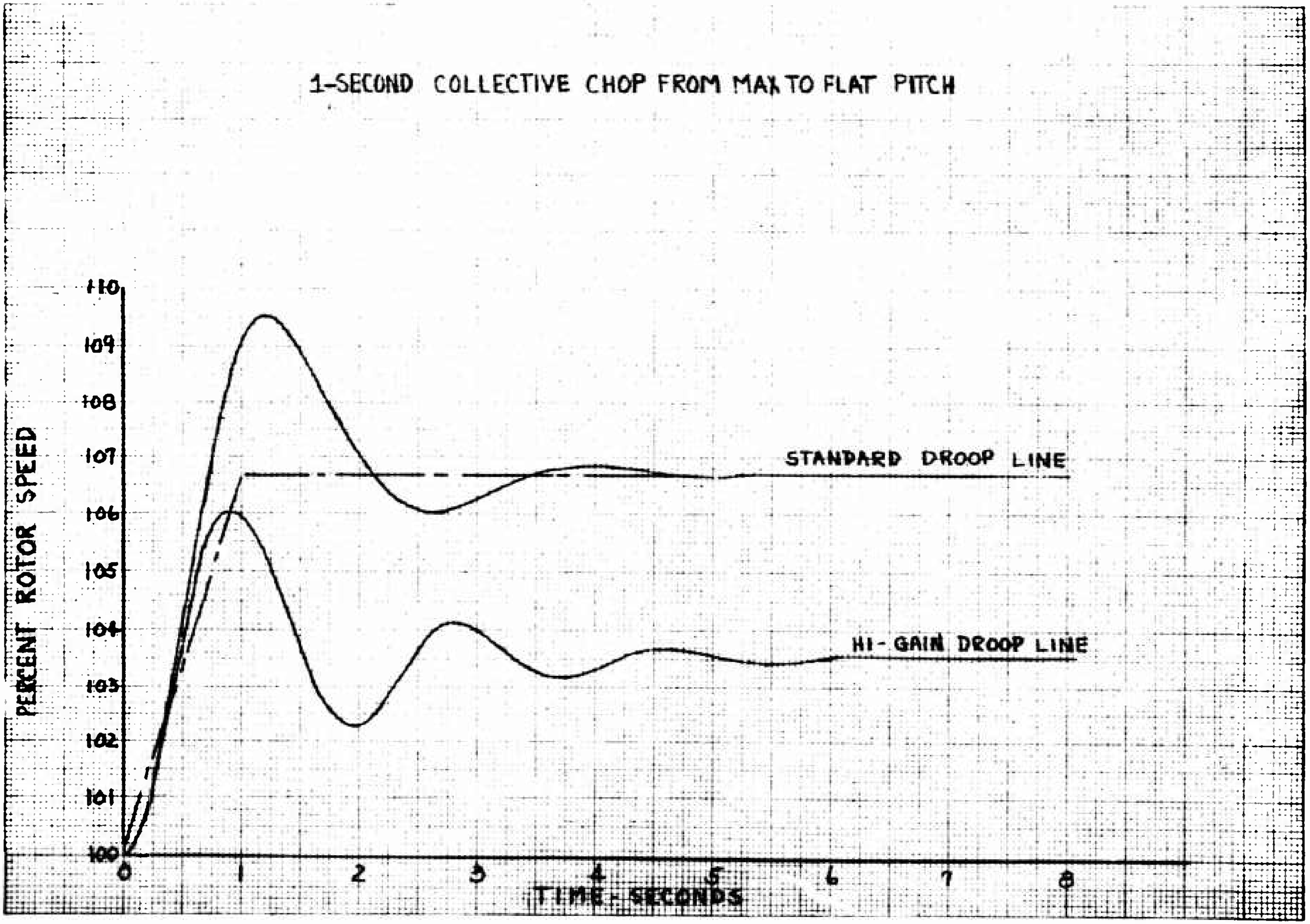


Figure 36. Power Transients Without Load Signal Compensation

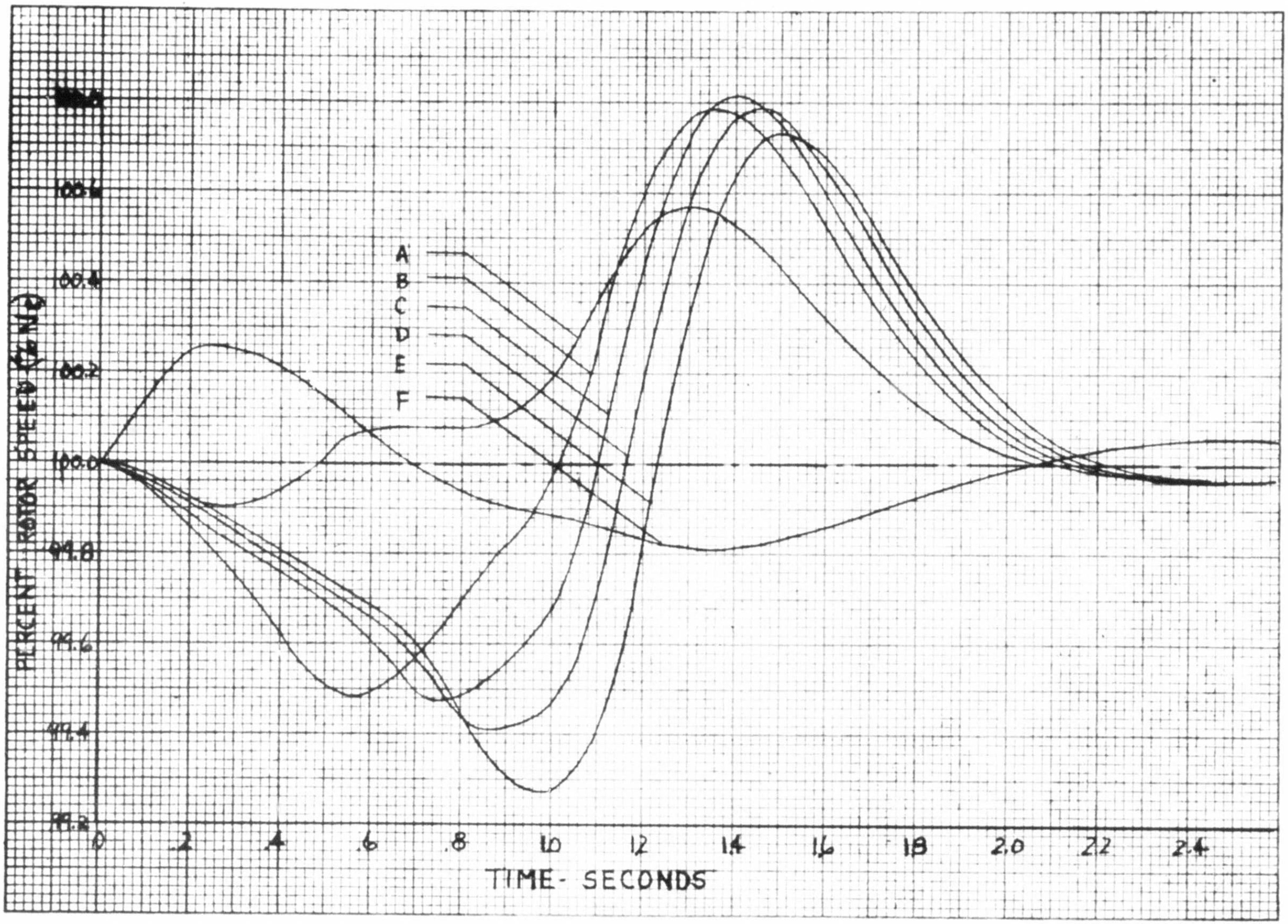


Figure 37. Power Transients with Load Signal Compensation

FAILURE ANALYSIS

INTRODUCTION

The failure analysis is considered in two parts: the first is engine failure and the subsequent operation of the diverter valve and tip nozzles; the second is failure of elements of the control system. These two are considered separately in this section.

ENGINE FAILURE

General

Two cases of engine failure were considered: a single-engine failure in the four-engine system and a double-engine failure in the four-engine system. The latter was used to simulate the single-engine failure in the two-engine system. Failures at part load and at full load were simulated and the results compared.

The DYNASAR program was used to simulate engine failure with the diverter valve block diagram as shown in Figure 17. The diverter valve dynamics and performance were obtained from the work performed under Air Force Contract AF33(600)-40862, using the J85 engine.

Engine failures were simulated by chopping the throttle on the engine(s) required. This simulates what would happen on combustor blowout and also approximates a high-speed stall.

The program was run with the Ng speed coordinator included, but a description of the operation of the system without this facility is also given.

Results and Discussion

The results of the engine failure analysis are shown in Figures 38 through 53 for the failure of one engine in the four-engine system and Figures 54 through 57 for the failure of two engines in the four-engine system.

The description of the operation of systems below is specifically referred to the four-engine system but the comments apply equally to the two-engine system. The numbered paragraphs below refer to the critical points during the transient as shown in the figures.

(a) Maximum Load-Divert in 0 Seconds (Figures 38 and 39)

1. The diverter valve operating time of 0.5 second does not affect the performance since the gas follows the line of least resistance and flows through the diverter valve very shortly after this is cracked. Thus, as the failed engine is diverted, the good engine(s) sees a large nozzle area and therefore accelerates along the droop line.

2. After 0.25 second, the nozzle area has achieved its correct value, causing the reverse of the previous action to occur.

3. Due to the reduction in rotor speed and hence the resulting lower pumping effect, the good engine(s) feels a higher back pressure, and hence the speed reduces along the droop line until stable operation is reached.

(b) Maximum Load-Divert in 1.5 Seconds (Figures 42 and 43)

1. The Ng coordinator senses the speed differential between the engines and reduces the Wf/P3 on the good engine(s) by 15 percent – its limit of authority.

2. The good engine(s) feels the reduced pressure and hence accelerates along the modified droop line.

3. The diverter valve opens, simultaneously cancelling the Ng coordinator signal from the failed engine.

4. Cancellation of the Ng coordinator signal causes the good engine(s) governor droop characteristic to return to the original level, but the increased nozzle area, as in paragraph (a), causes the good engine(s) to continue acceleration.

5. The tip nozzle is fully closed and the operation is now the same as (a)3 with a reduced steady-state running speed and higher temperatures.

Without the Ng coordinator, the engine(s) would follow the dotted line (1) to (4) on Figures 42 and 43 since the only influence on the engine(s) would be the reduced back pressure.

(c) Part Load-Divert in 0 Seconds (Figures 46 and 47)

1. Initially the throttle setting is such that the engines are below topping. The failed engine is diverted and as in (a)3 the good engine(s) accelerates.

2. The tip nozzles are closed and the fuel flow is increased in response to the demand from the rotor speed governor.

3. The fuel flow reaches the droop line and the speed increases until the steady-state speed at topping is reached. The overshoot that occurs during this phase is the same as that experienced on a normal throttle burst.

4. As before, the steady-state Ng speed is low due to the reduced rotor speed; also, the final steady-state T5 is above topping.

(d) Part Load-Divert in 1.5 Seconds (Figures 50 and 51)

1. Initially the throttle setting is below topping and the Ng coordinator reduces the Wf/P3 characteristic by 15 percent as in paragraph (b).

2. The rotor speed governor causes the fuel flow to increase to within 0.85 of the normal acceleration schedule, and the engine accelerates to the droop line.

3. The good engine(s) is still feeling the reduced back pressure and continues to accelerate along the droop line as in (b)2.

4. The remainder of the cycle continues as in (b)3.

Without the Ng coordinator, the rotor speed governor causes the good engine(s) to accelerate along the original acceleration schedule. The transient temperatures are again those experienced in a normal throttle burst.

Figures 40, 44, 48, 52, 54, and 57 show the relationship between the speed of the failed engine(s) and that of the good engines. From these it can be seen that the deceleration of the failed engine is so rapid that the good engines would exhaust through the failed engine, causing a large loss of power. It is therefore desirous that the control of the diversion sequence be automatic, and from these figures it is obvious that a differential speed signal similar to the Ng coordinator signal can be used.

The reduction in rotor speed and loss of rotor torque is shown in Figures 41, 45, 49, 53, 55, and 56.

Considering the single-engine failure in the four-engine system, it can be seen that the loss in torque following the failure is 38 percent. This is higher than expected due to the reduced pumping effect and hence higher pressure drop in the rotor duct. By reduction of the rotor cyclic pitch, the rotor speed is increased, thereby increasing the torque at the rotor. These same qualitative comments apply to the failure of two engines in the four-engine system.

The failure of one engine in the two-engine system will not exactly correspond to the failure of two in four due to the lower rotor inertia of the smaller system. Thus the rotor speed will stabilize at the lower value much faster.

Failure of Diverter Valve System

Two failures were considered possible for the four-engine system:

1. Failure of the tip nozzle open with three engines running.
2. Failure of the tip nozzle closed with four engines running.

Considering case 1, it is obvious that the increase in area reduces the pressure ratio across the nozzle which causes a power loss in excess of 40 percent of the power available from three engines.

Case 2 causes an increase in exhaust pressure which results in an increase in temperature. The increase is governed by the possible increase in Wf/P3 along the governor droop line before the acceleration schedule is reached. In this case the engine decelerates along the acceleration schedule and the temperature increase is 300°F.

Recommendations

1. Operation of the diversion sequence should be automatic in order to prevent flow reversal in the failed engine.

2. The rotor loading should be reduced in order to reestablish the rotor efficiency and reduce the gas generator temperatures T5.

3. The diverter valve and tip nozzle should be prime reliable due to the serious results of failure.

SYSTEM FAILURE ANALYSIS

General

The T64 multi-gas generator with a common duct requires two new control subsystems. The failure of each of these is considered separately.

Acceleration Control

The acceleration control has possibilities of inadvertent limiting or failing to limit in spite of component design which may reduce failure possibilities to an acceptable level.

Inadvertent reduction of fuel flow may delay acceleration of one or more engines and defeat roll-back protection. The effect upon acceleration time is inconsequential with respect to airframe requirements.

If roll-back occurs, normal operation can quickly be obtained by simple pilot corrective action. The rolled-back engine will be readily identified by relatively low rpm and high temperature. The pilot will then operate the diverter valve switch, whereupon the engine will immediately accelerate to approximately the same speed as the other engines. The pilot can thus, after a pause of 2 or 3 seconds, release the diverter switch. The diverter switch for convenience might be an integral part of the engine control lever, mounted on the lever but actuated not as a function of lever angle.

Rotor Governing Failure

Failures of the rotor speed sensor and connection to the fuel controls, which falsely indicate an underspeed condition, act to increase engine power through normal action of the fuel control. A large underspeed signal or loss of signal will increase engine power to the temperature limit. This condition may be relieved by the pilot's retarding the control lever of the affected engine. A partial reduction, if any, might be preferable, however, since roll-back protection of the limited engine would not be fully effective during subsequent collective pitch bursts.

Gross failure of rotor speed sensing, tending to overspeed the rotor, is protected by the overspeed control which acts independently of the normal rotor speed control system.

False indications of overspeed are of quite negligible possibility. The sensor and coupling have no possibility of overspeeding. Failures of remote probability are required to obtain an overspeed signal in the fuel control. Inadvertent reduction of power due to failure in the rotor governing system is therefore of negligible possibility.

The following table (Table IX) and the associated notes give the description of the possible failures and the remedial action, if any, to be taken by the pilot.

Conclusions

The design of the control system is such that the possibility of failures is remote; and in the event of any failure, simple pilot action can rectify the control.

NOTES FOR TABLE IX

Failure Probabilities, Effects, and Corrective Means

1. The reduction of fuel flow by the acceleration control is limited to 15 percent. (No additional cutback for very large overspeeds.)

2. Acceleration limiter Ng signal downward failure results in fail-safe, high indicated Ng. (Other engines unaffected — this engine may accelerate less rapidly or roll-back.)

3. Switch for diverter valve (on engine control lever) provides for acceleration and reloading of rolled-back engine within a few seconds after pilot operates switch to divert and reload.

4. If an engine has rolled back and been reloaded, subsequent rotor loadings should be gradual to avoid demand for rapid acceleration and repeated roll-back.

5. Redundant design of minimum Ng signal selector assures that (1) loss of an Ng signal has the effect of a very high Ng signal and (2) false low Ng reference required double failure.

6. Design of Ng unbalance and limiting circuits employs either (1) redundancy and/or (2) fail safety to minimize possibility of failures in the limiting direction.

7. System uses engine-furnished power and may (1) switch to airframe power in the event of power loss or (2) employ redundant alternator windings and connections to the control.

8. If rotor speed sensing utilizes electrical components, rotor speed sensor dual windings and connections may be employed to provide signal in spite of any single airframe open or short circuit.

9. Possibility of false overspeed signals are remote due to the nature and design of electrical, mechanical, and hydraulic sensors and couplings. If electrical circuits are utilized, redundancy may be incorporated.

TABLE IX
ACCELERATION CONTROL FAILURE ANALYSIS

Failure	Consequence	Notes	Comment
Ng Signal			
Downward	Loss of roll-back protection. Engines accelerate less rapidly than otherwise.	3, 4, 2	Fail-safe circuitry & redundancy make loss of signal & false low indicated rpm likelihood negligible.
Upward	Loss of roll-back protection. Engine may accelerate more rapidly than otherwise.	11, 3, 4	Negligible in view of nature of components.
Ng Comparator			
Downward Reference	Engines accelerate less rapidly. Loss of roll-back protection.	3, 4, 5	Negligible as a result of either (1) nature of components or (2) redundancy.
Upward	Engines may accelerate more rapidly. Loss of roll-back protection.	3, 4	Small in view of quality of components.
Signal Loss	Loss of roll-back protection.	5	Component fail-safe design results in overspeed signal.
Ng Error/Limiter			
Decrease Wf/P3 Inadvertently.	Loss of roll-back protection. Engine may accelerate less rapidly than otherwise.	3, 4 6	Circuit design such that failures tend not to decrease Wf/P3.
Fails to Decrease Wf/P3	Engine may accelerate more rapidly than otherwise.		Small possibility in view of quality of components.
Loss of Signal	Engine may accelerate more rapidly than otherwise.	6	Component fail-safe design results in underspeed signal.
Overspeed Signal	Loss of roll-back protection.	11, 3, 4	Negligible in view of quality components.
Underspeed Signal	Engine may accelerate more rapidly.		Small possibility – quality components
Power Loss	Loss of roll-back protection.	3, 4, 7	Redundant power source.
Loss of Speed Signal			
[illegible]	All engines accelerate to [illegible]		Recommend maximizing independence [illegible] to speed sensor.
[illegible]	[illegible] may accelerate more rapidly than otherwise.		[illegible] nature of components.

	rapidly than otherwise.		ponents.
Ng Comparator			
Downward Reference	Engines accelerate less rapidly. Loss of roll-back protection.	3, 4, 5	Negligible as a result of either (1) nature of components or (2) redundancy.
Upward	Engines may accelerate more rapidly. Loss of roll-back protection.	3, 4	Small in view of quality of components.
Signal Loss	Loss of roll-back protection.	5	Component fail-safe design results in overspeed signal.
Ng Error/Limiter			
Decrease Wf/P3 Inadvertently.	Loss of roll-back protection. Engine may accelerate less rapidly than otherwise.	3, 4 6	Circuit design such that failures tend not to decrease Wf/P3.
Fails to Decrease Wf/P3	Engine may accelerate more rapidly than otherwise.		Small possibility in view of quality of components.
Loss of Signal	Engine may accelerate more rapidly than otherwise.	6	Component fail-safe design results in underspeed signal.
Overspeed Signal	Loss of roll-back protection.	11, 3, 4	Negligible in view of quality components.
Underspeed Signal	Engine may accelerate more rapidly.		Small possibility – quality components
Power Loss	Loss of roll-back protection.	3, 4, 7	Redundant power source.
Loss of Speed Signal			
All Engines	All engines accelerate to topping. Rotor overspeed limiter.	9	Recommend maximizing independence of connections to speed sensor.
Single Engine	Engine accelerated to topping. Other engines decrease Ng to govern rotor rpm.	9	Pilot can reduce T5 and balance engines by retarding engine control lever.
Governor Failure			
False Underspeed	Engine accelerated to topping. Other engines decrease Ng to govern rotor rpm.		Pilot can reduce T5 and balance engines by retarding engine control lever.
False Overspeed	Probably roll-back of engine	11	Speed transmission and sensing components have remote possibility of overspeeding.

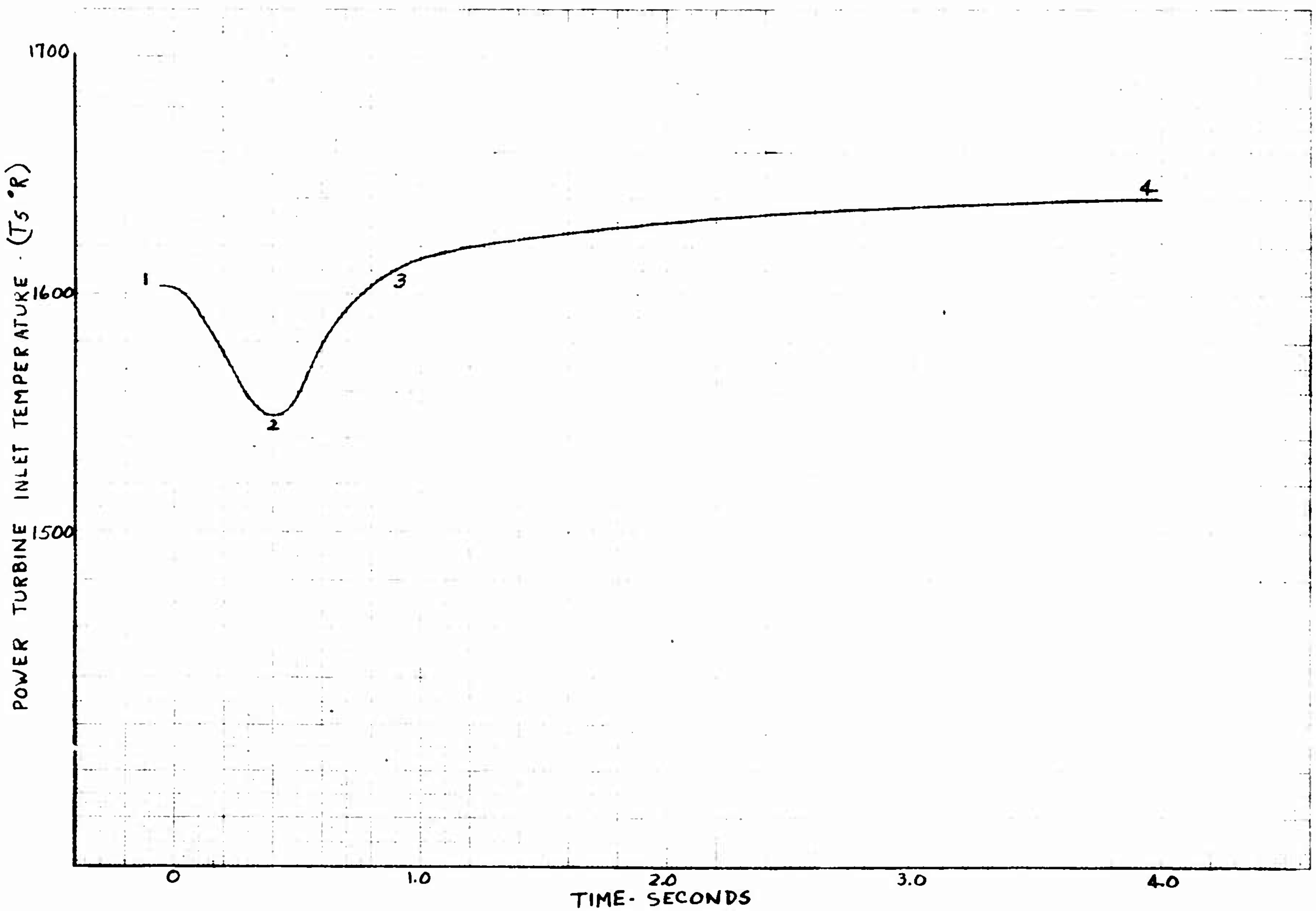


Figure 38. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 0 sec: T5 vs Time

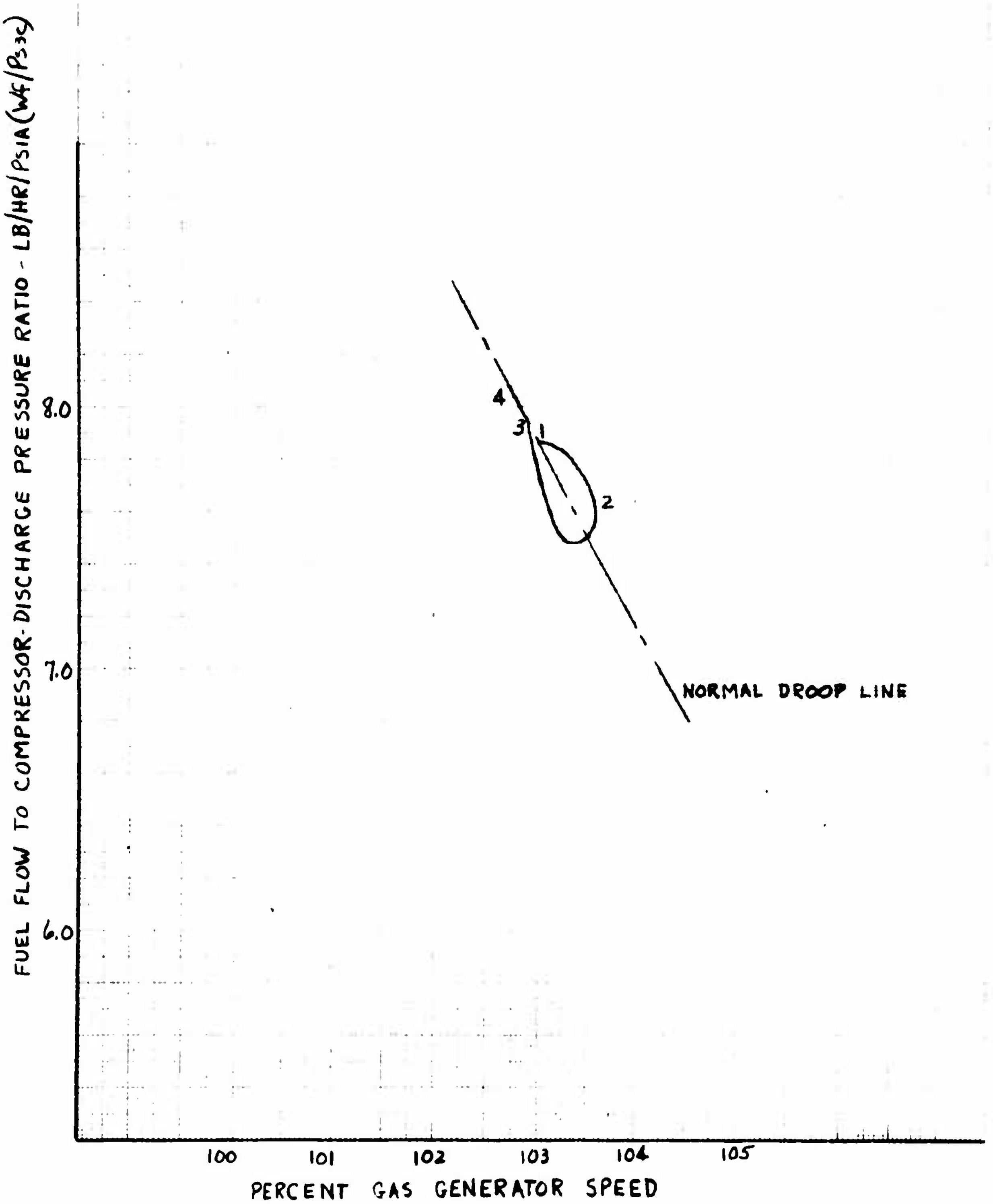


Figure 39. Failure Analysis; Four Engine System; Maximum Load; One Engine Failed; Divert in 0 Sec: Wf/Ps3c vs % Ng

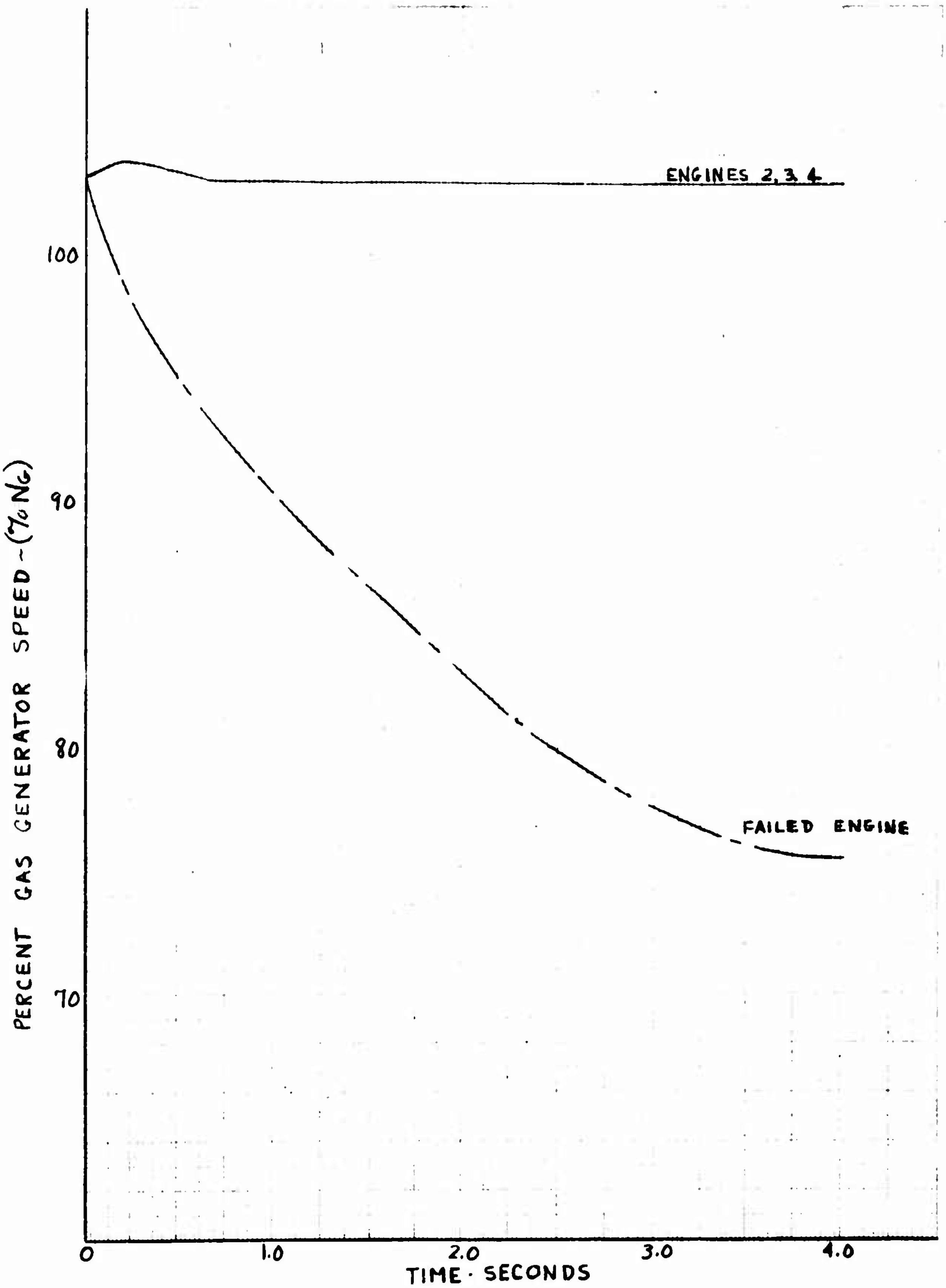


Figure 40. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 0 Sec: % Ng vs Time

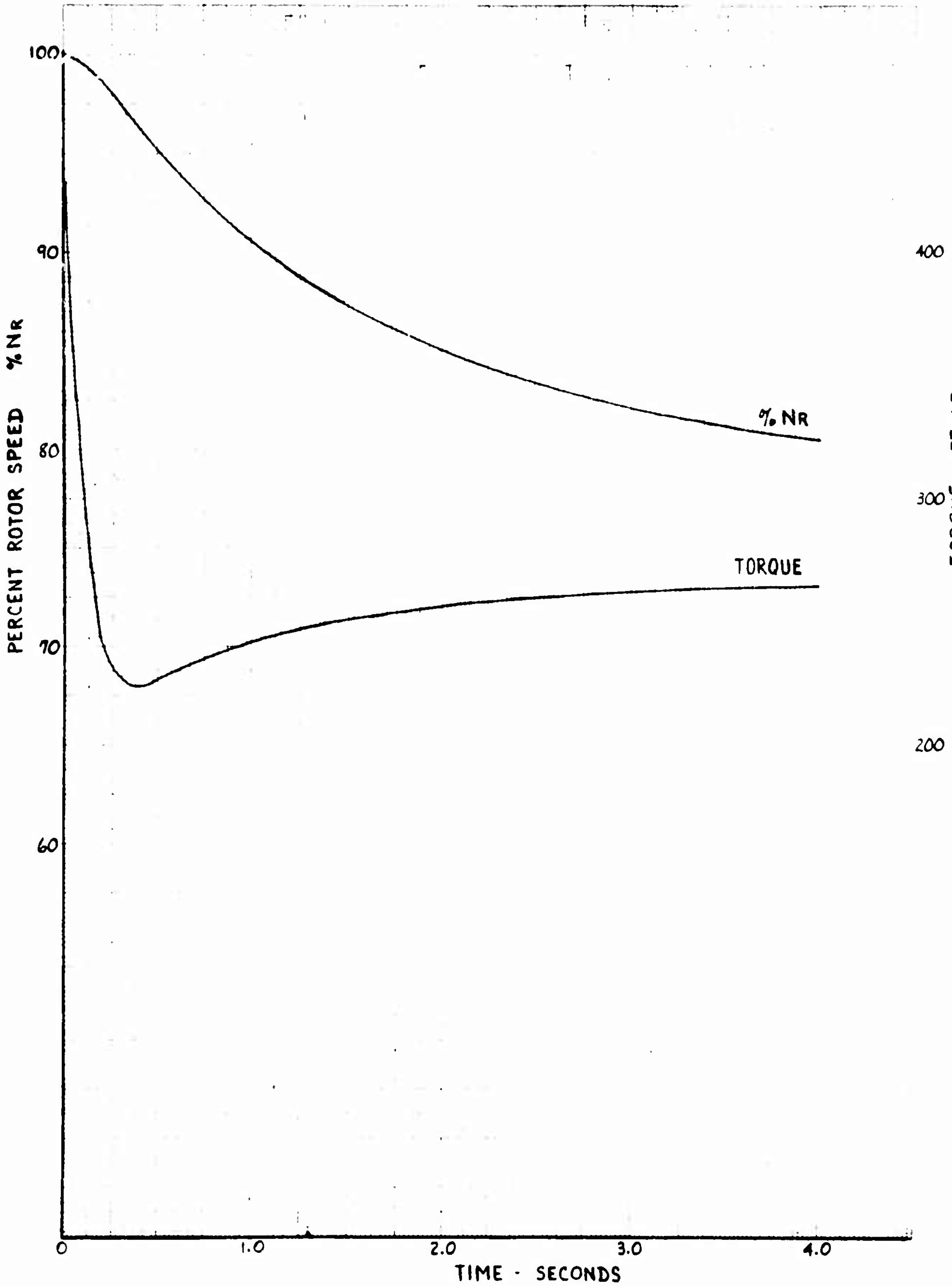


Figure 41. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 0 Sec: % Nr, τ vs Time

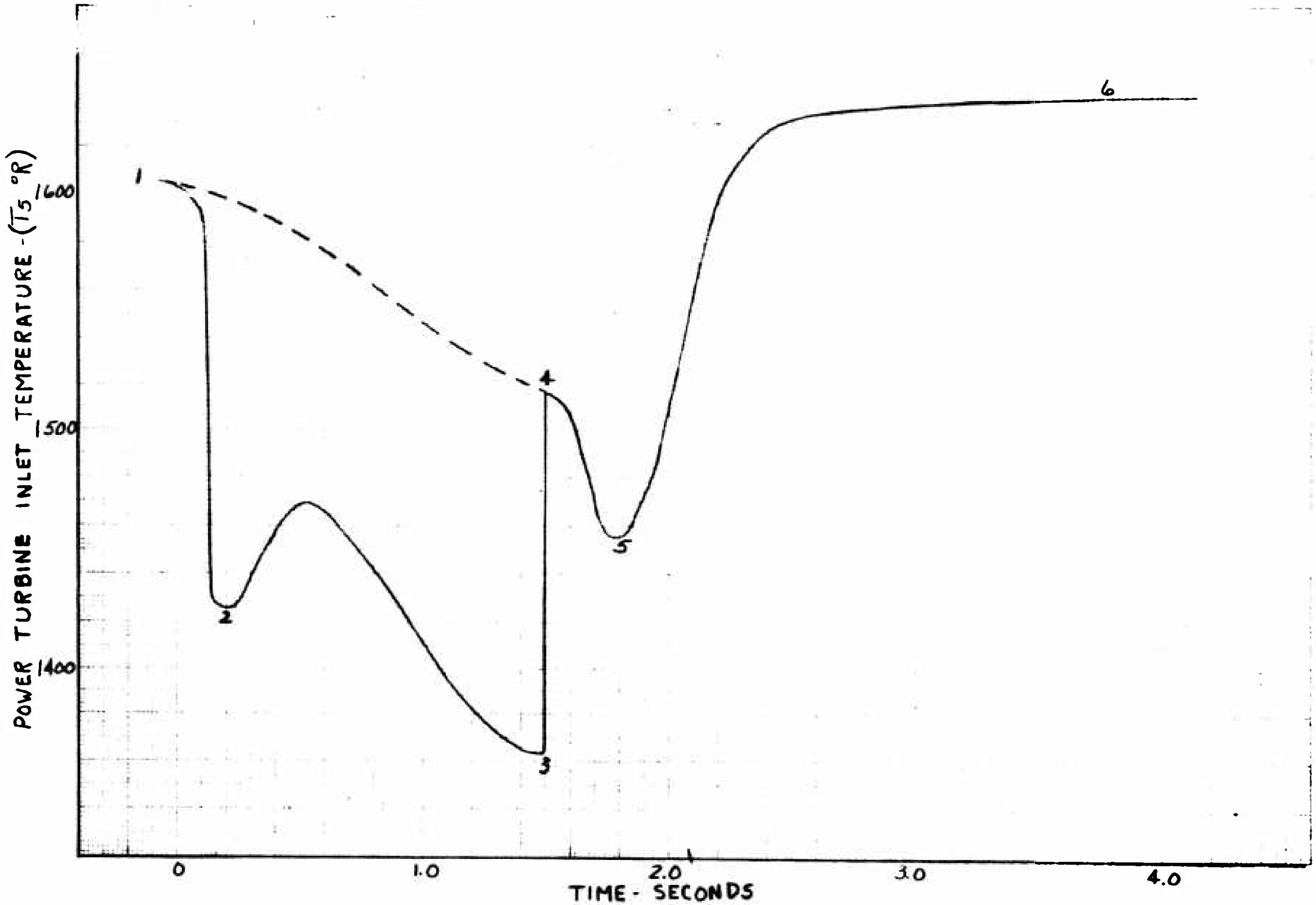


Figure 42. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 1.5 Sec: T5 vs Time

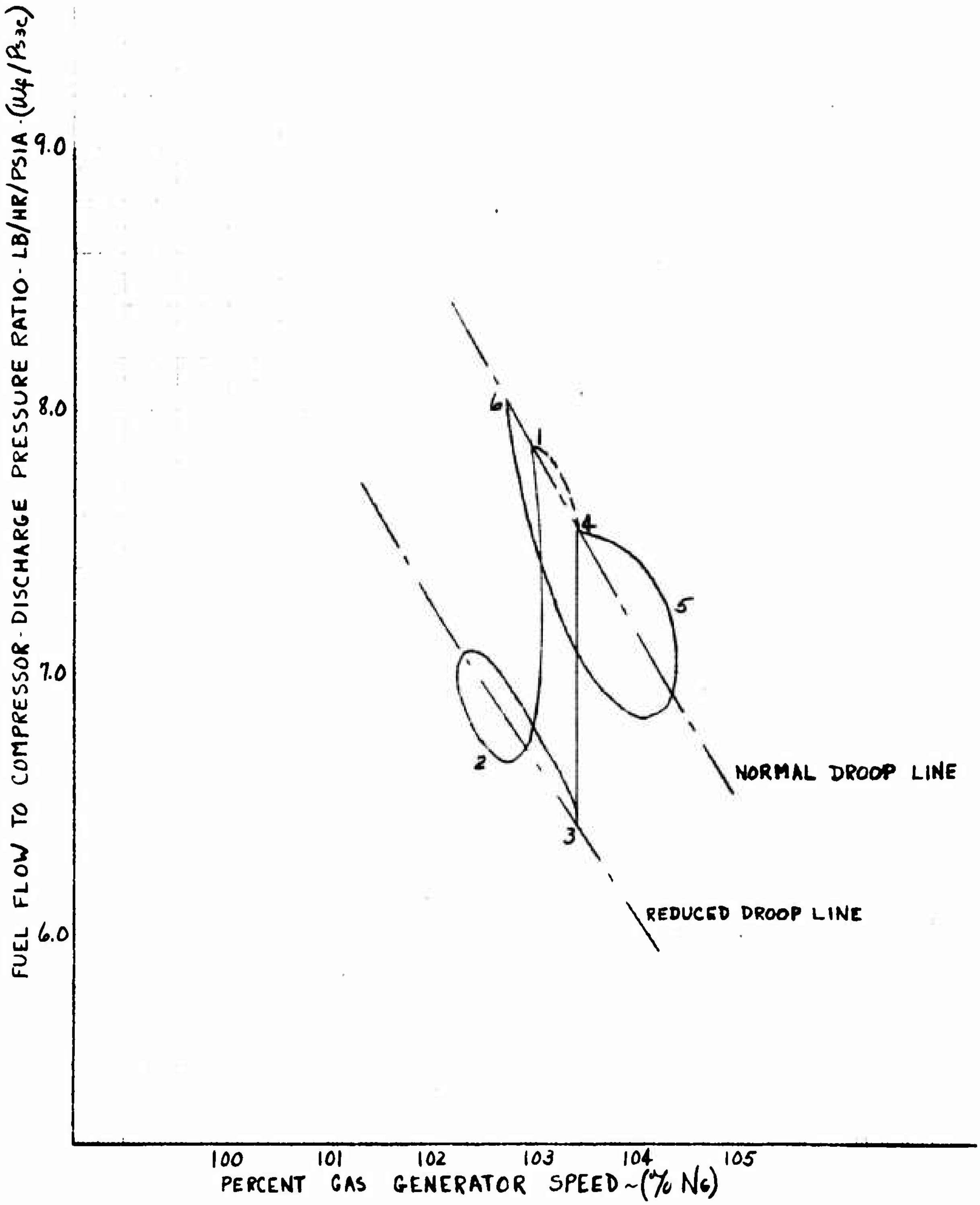


Figure 43. Failure Analysis; Four Engine System; Maximum Load; One Engine Failed; Divert in 1.5 Sec: Wf/Ps3c vs % Ng

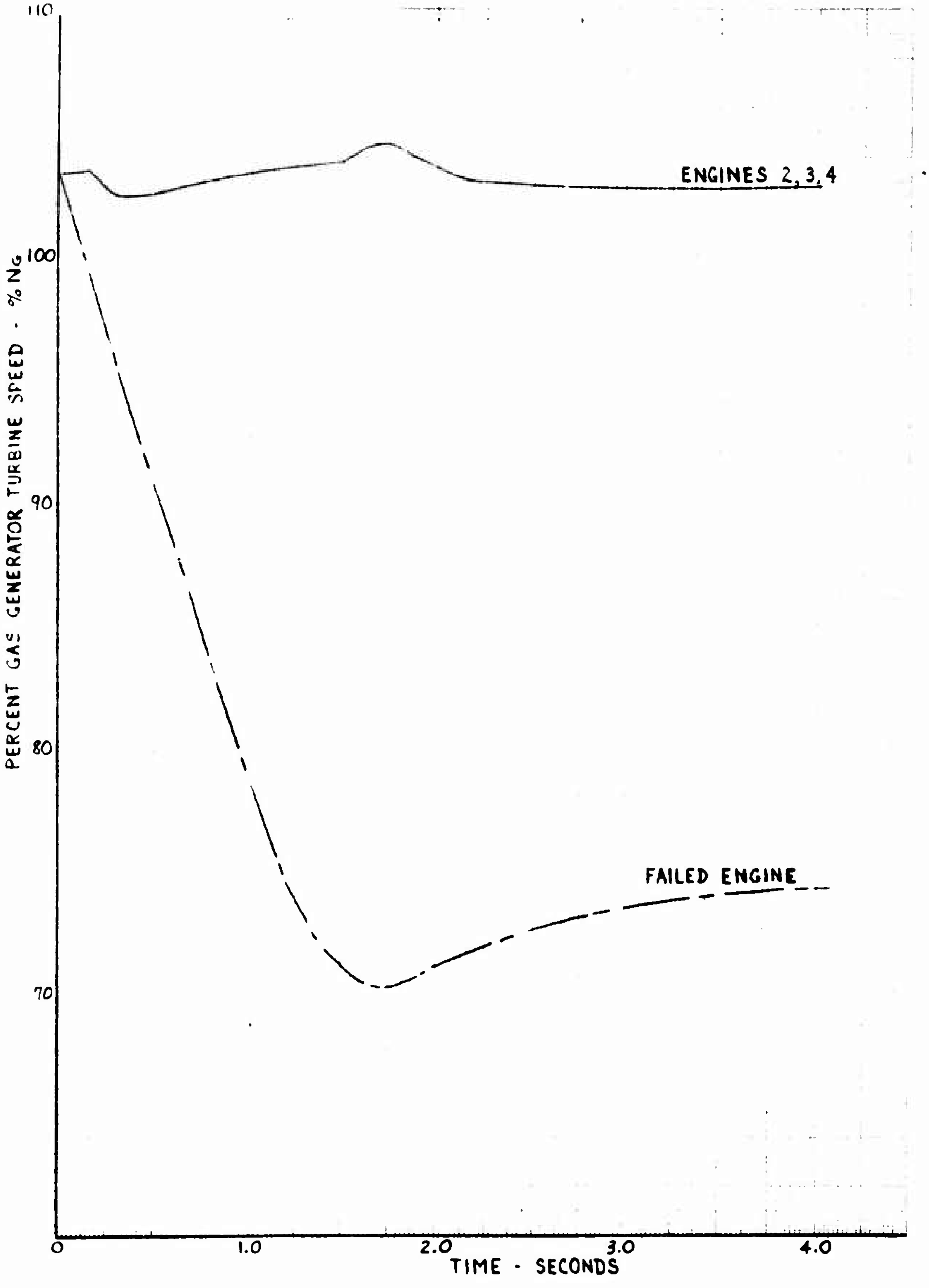


Figure 44. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 1.5 Sec; % Ng vs Time

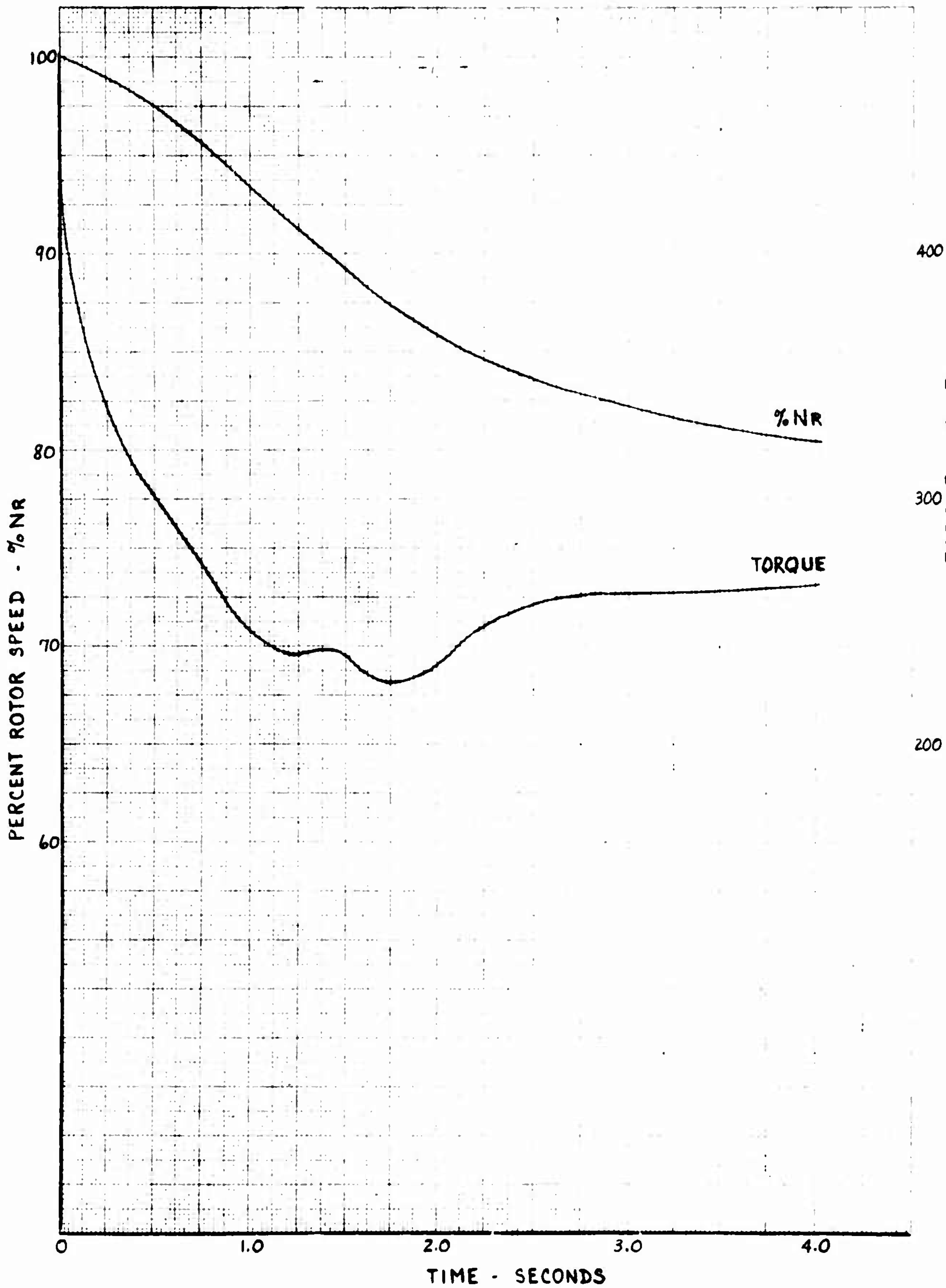


Figure 45. Failure Analysis; Four-Engine System; Maximum Load; One Engine Failed; Divert in 1.5 Sec: % Nr, τ vs Time

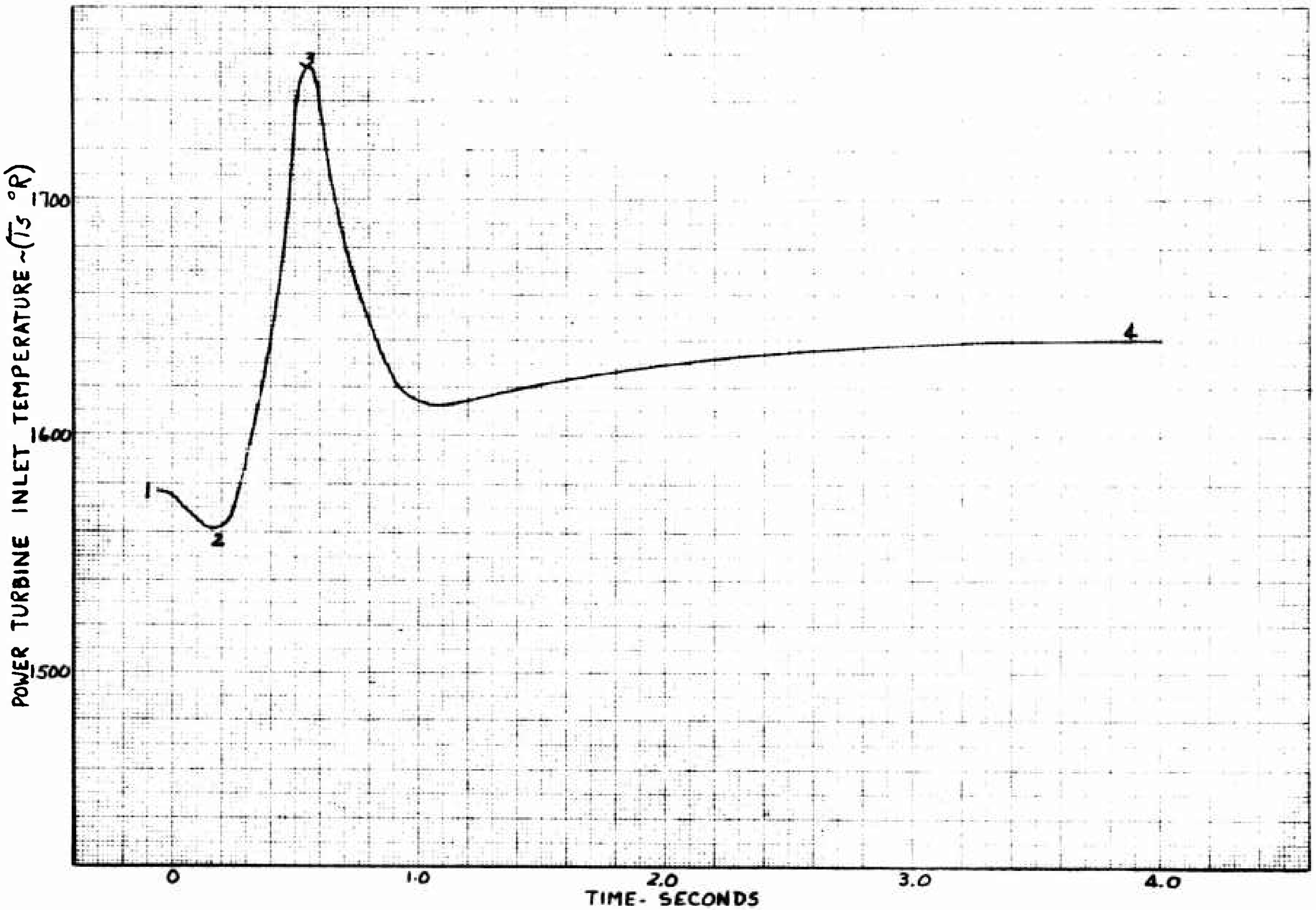


Figure 46. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 0 Sec: T5 vs Time

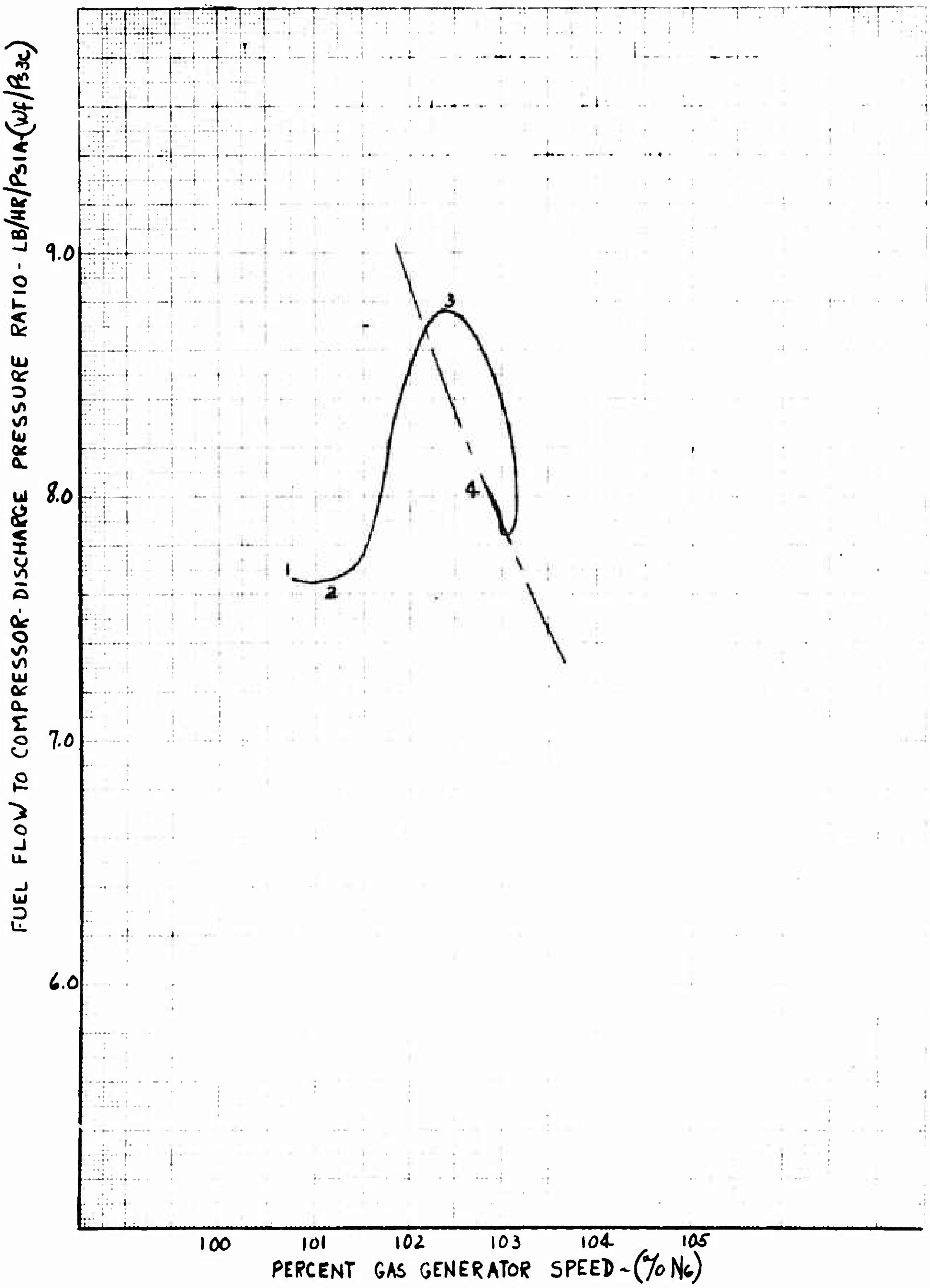


Figure 47. Failure Analysis; Four Engine System; Part Load; One Engine Failed; Divert in 0 Sec: W_f/P_{s3c} vs % Ng

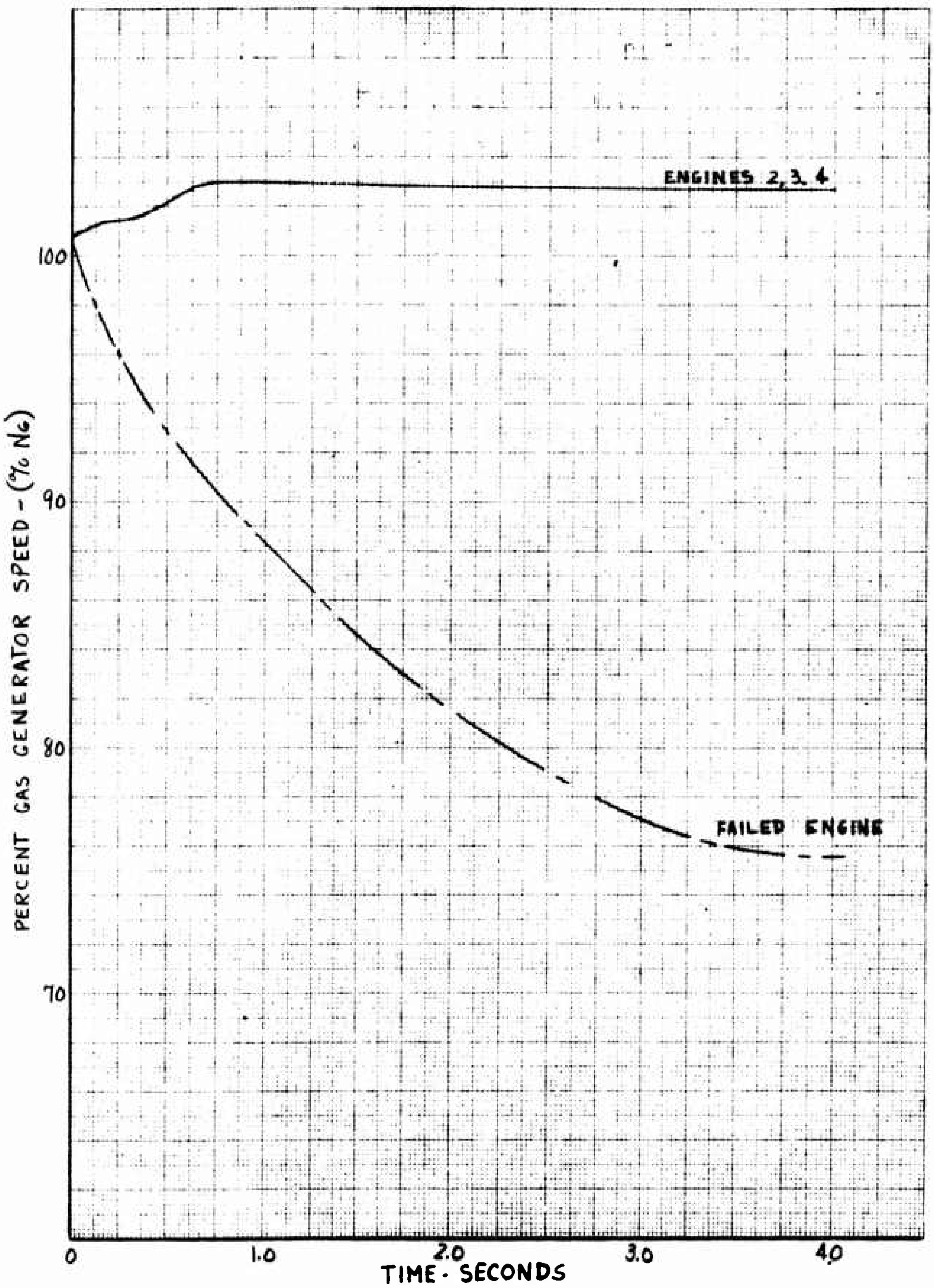


Figure 48. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 0 Sec; % Ng vs Time

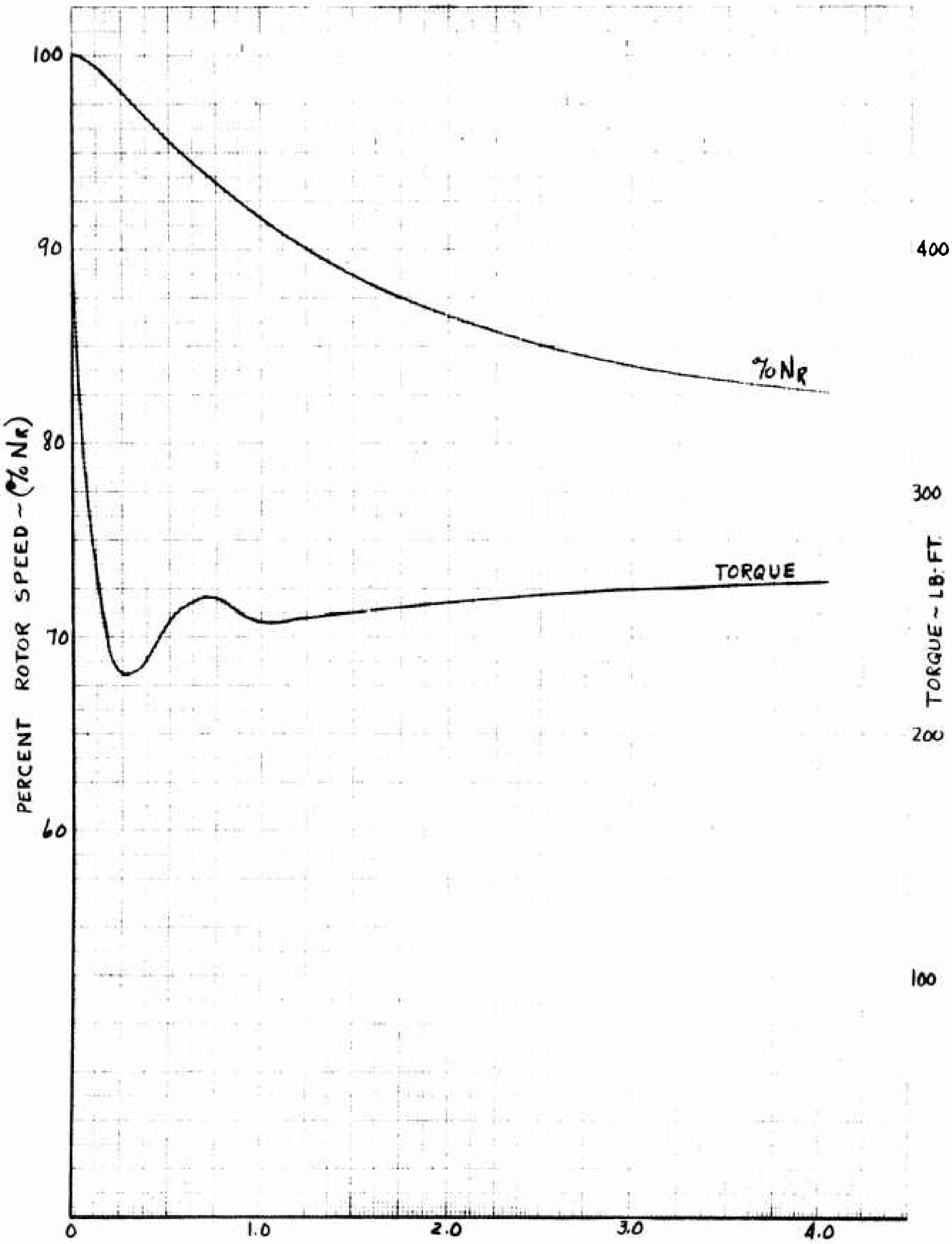


Figure 49. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 0 Sec: % Nr, τ vs Time

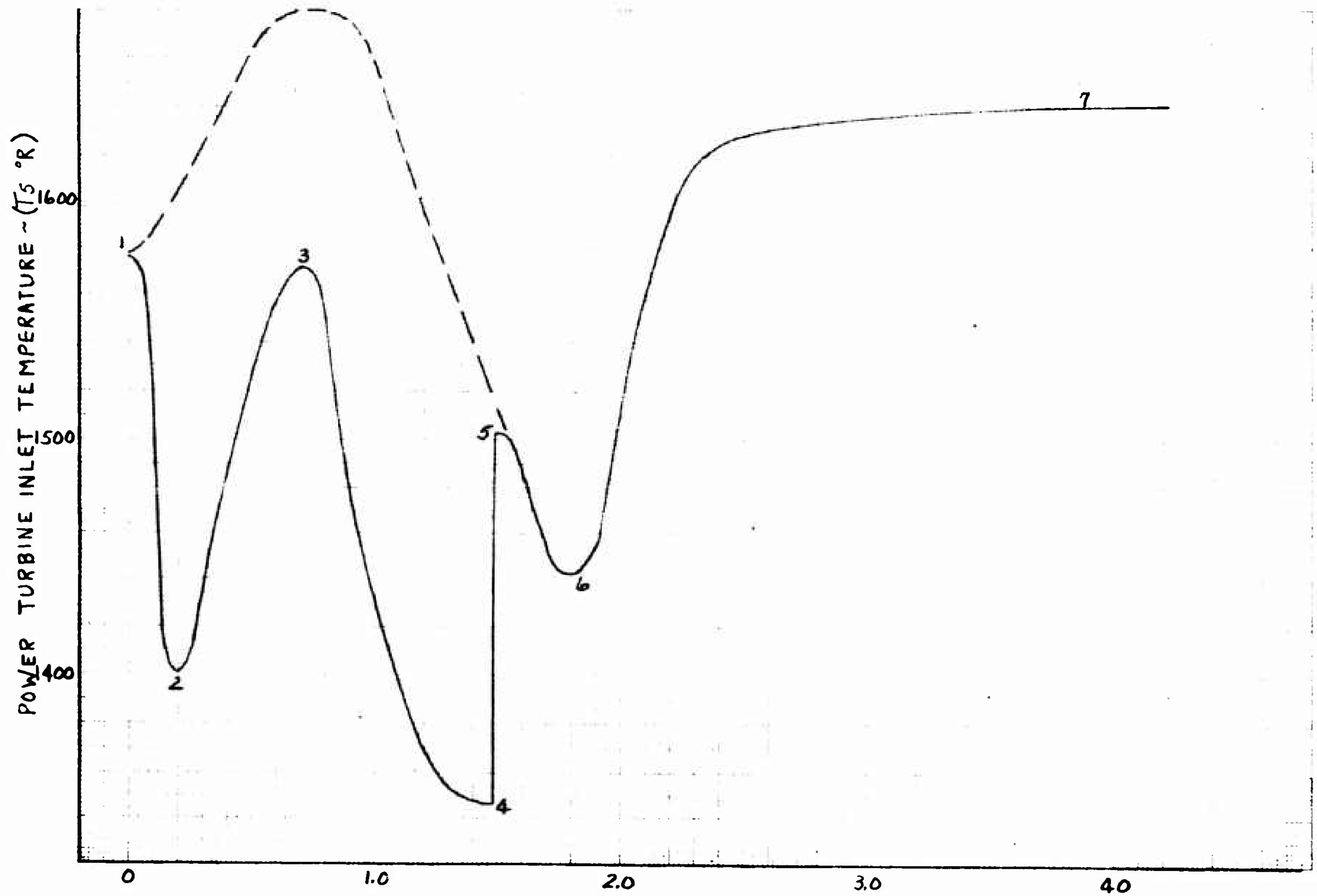


Figure 50. Failure Analysis; Four-Engine System, Part Load; One Engine Failed; Divert in 1.5 Sec: T5 vs Time

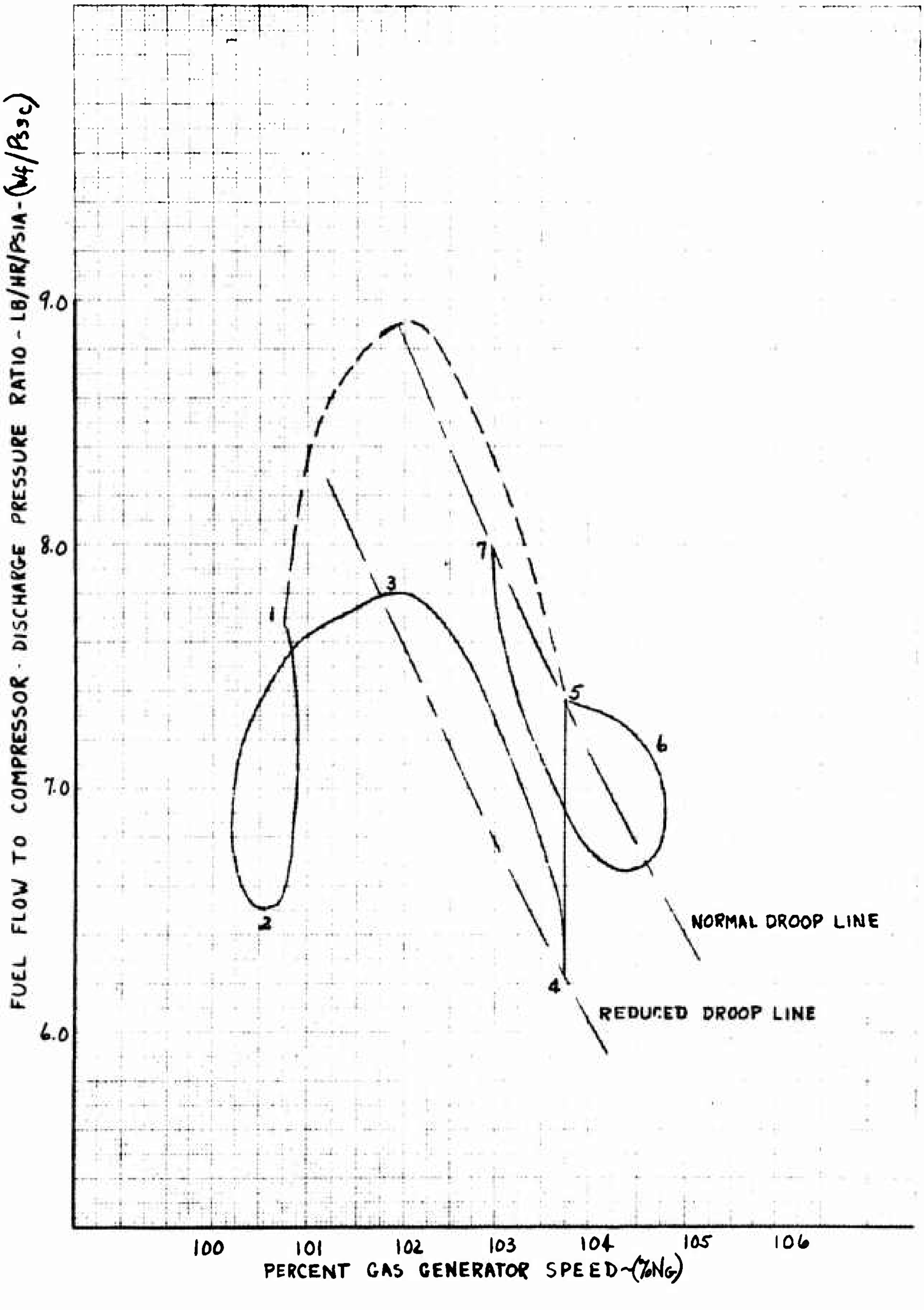


Figure 51. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 1.5 Sec: Wf/Ps3c vs Time

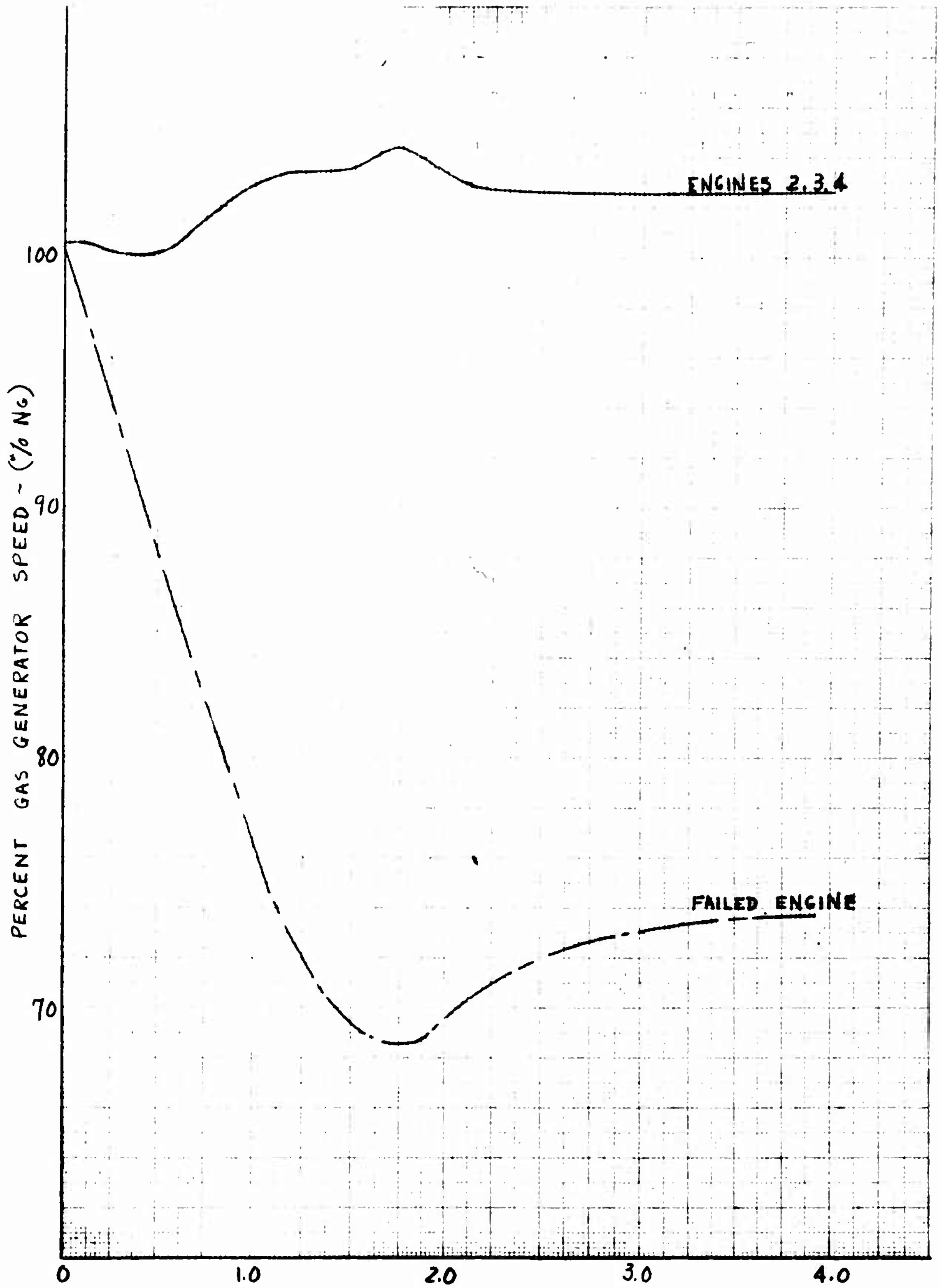


Figure 52. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 1.5 Sec: % Ng vs Time

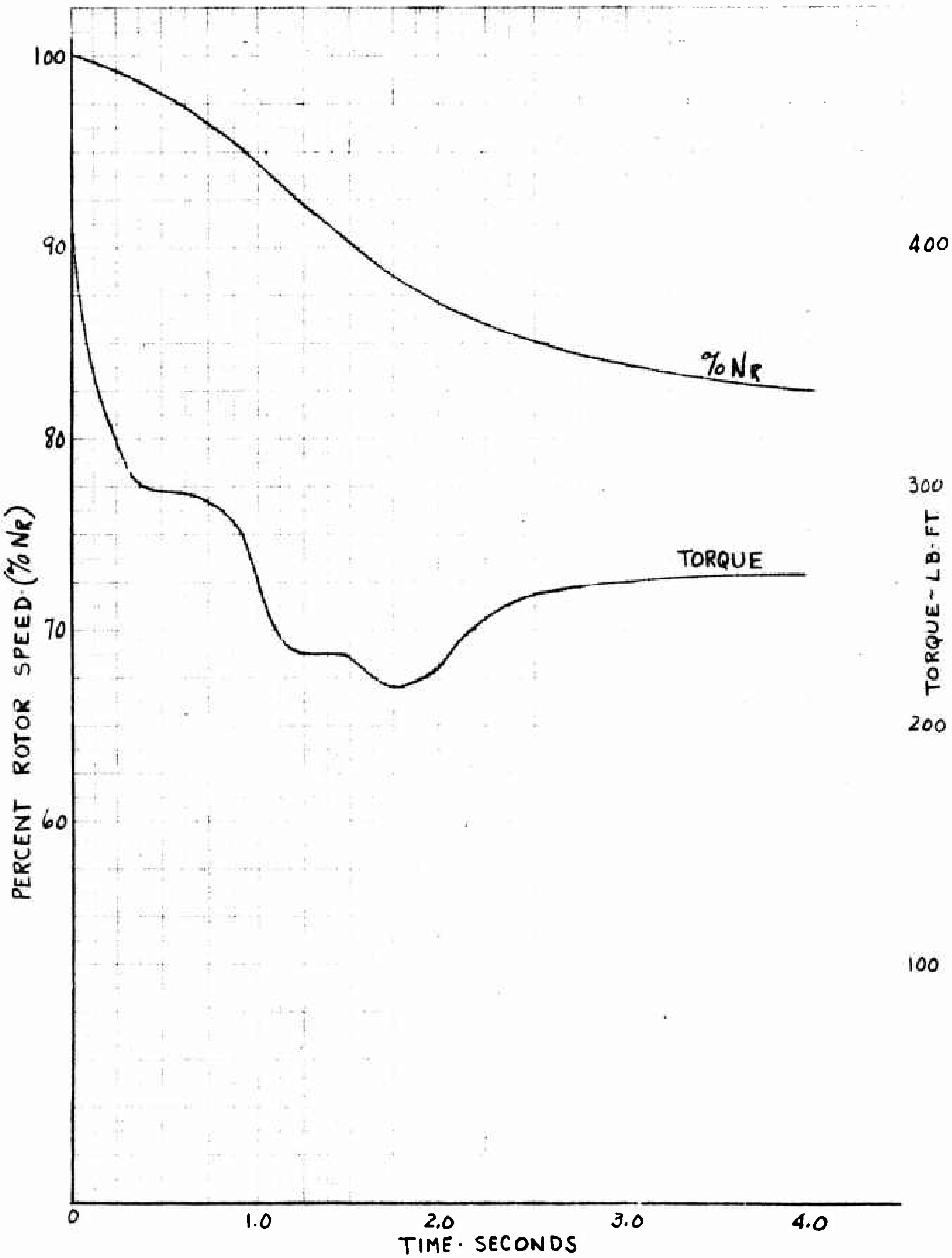


Figure 53. Failure Analysis; Four-Engine System; Part Load; One Engine Failed; Divert in 1.5 Sec: % Nr, τ vs Time

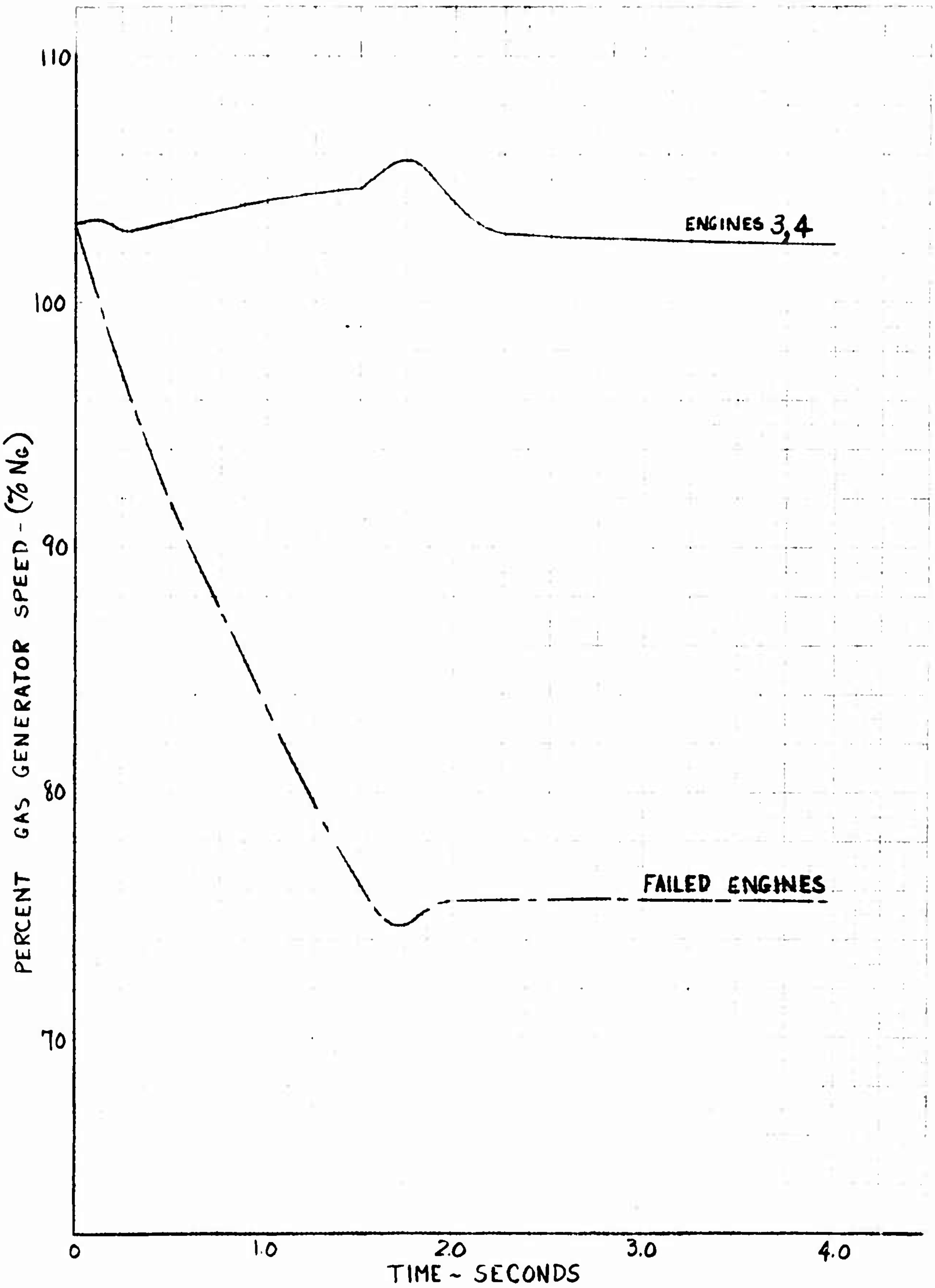


Figure 54. Failure Analysis; Four-Engine System; Maximum Load; Two Engines Failed; Divert in 1.5 Sec: % Ng vs Time

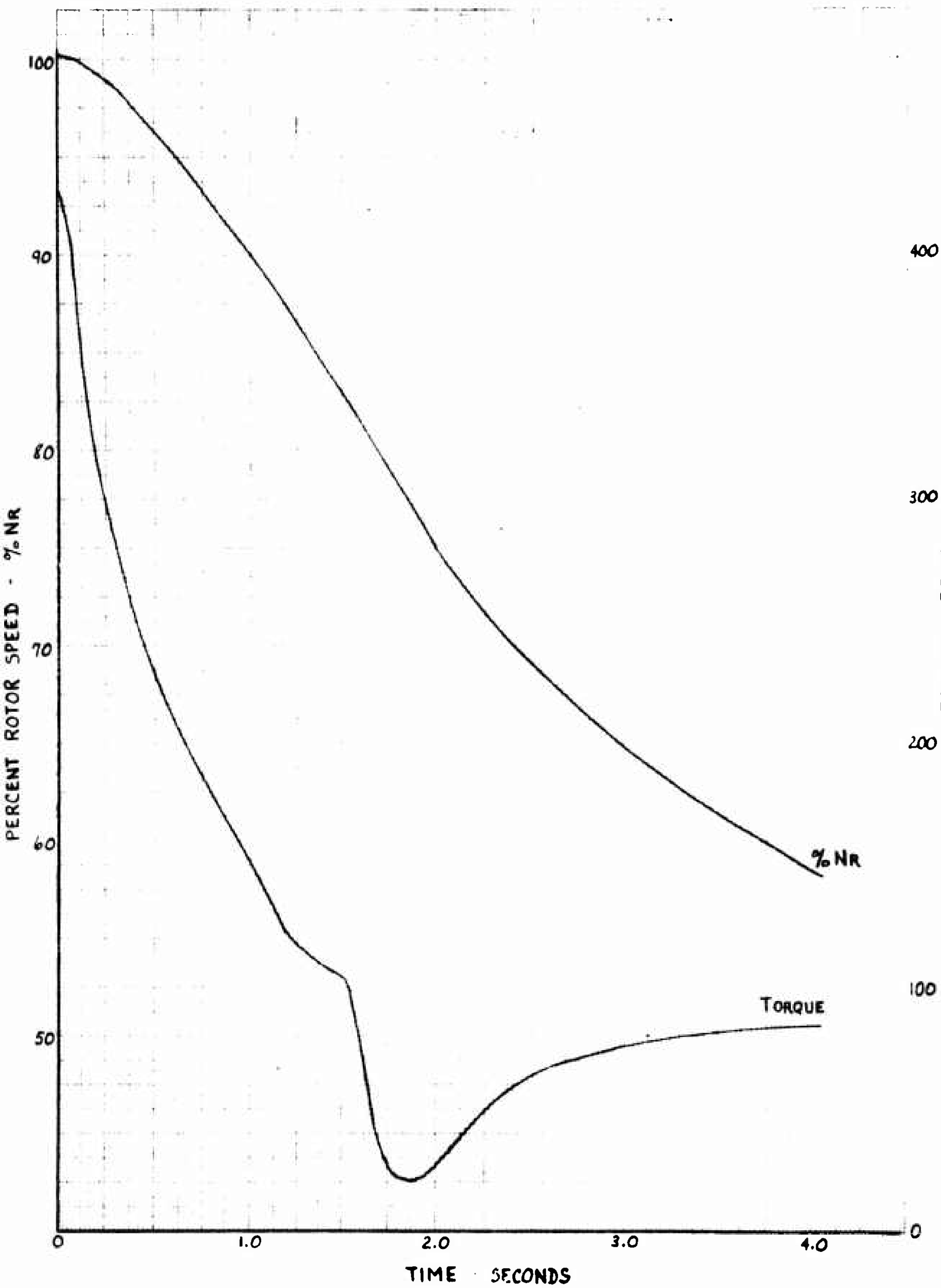


Figure 55. Failure Analysis; Four-Engine System; Maximum Load; Two Engines Failed; Divert in 1.5 Sec: % Nr, τ vs Time

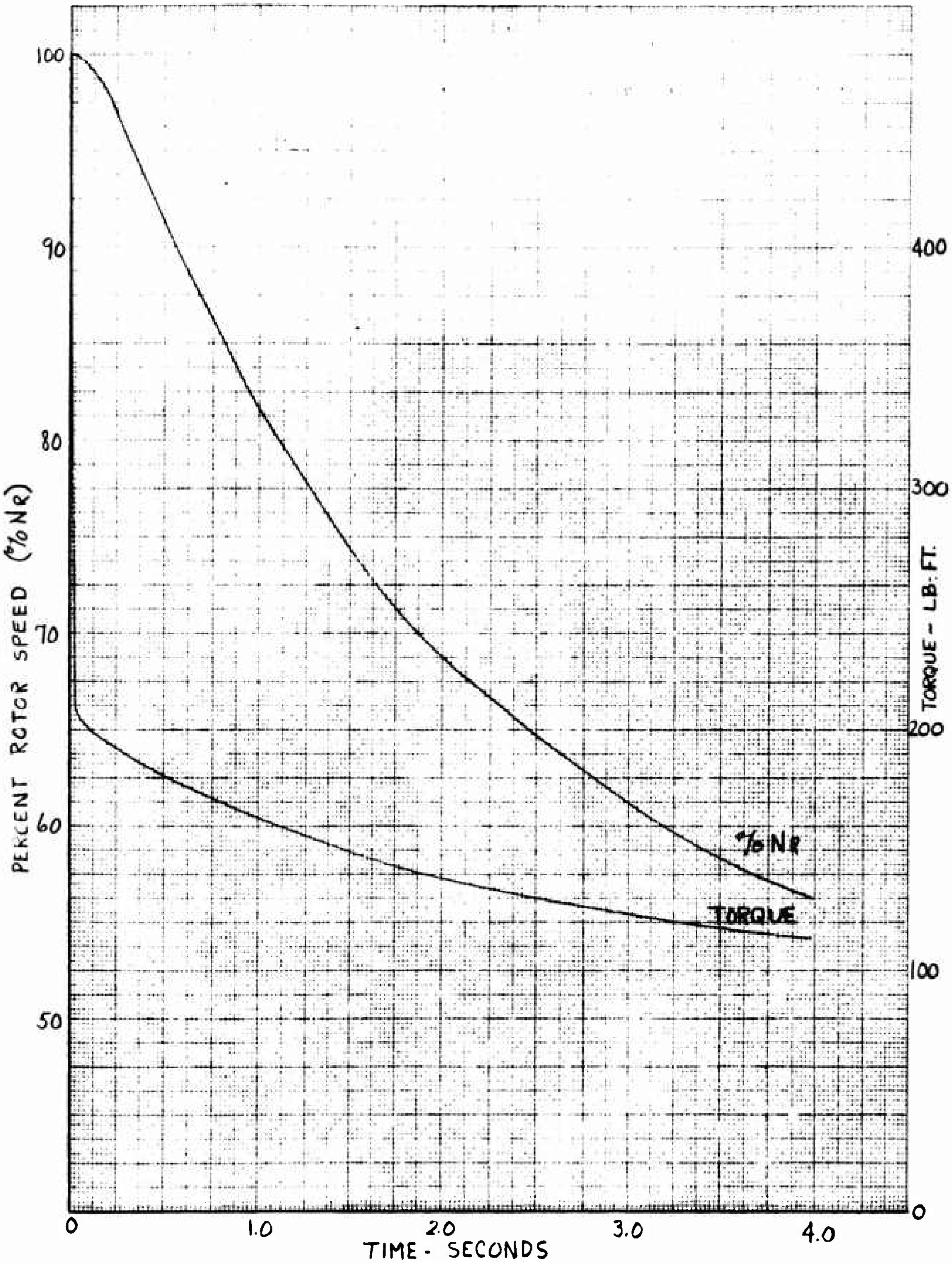


Figure 56. Failure Analysis; Four-Engine System; Maximum Load; Two Engines Failed; Divert in 0 Sec: % Nr vs Time

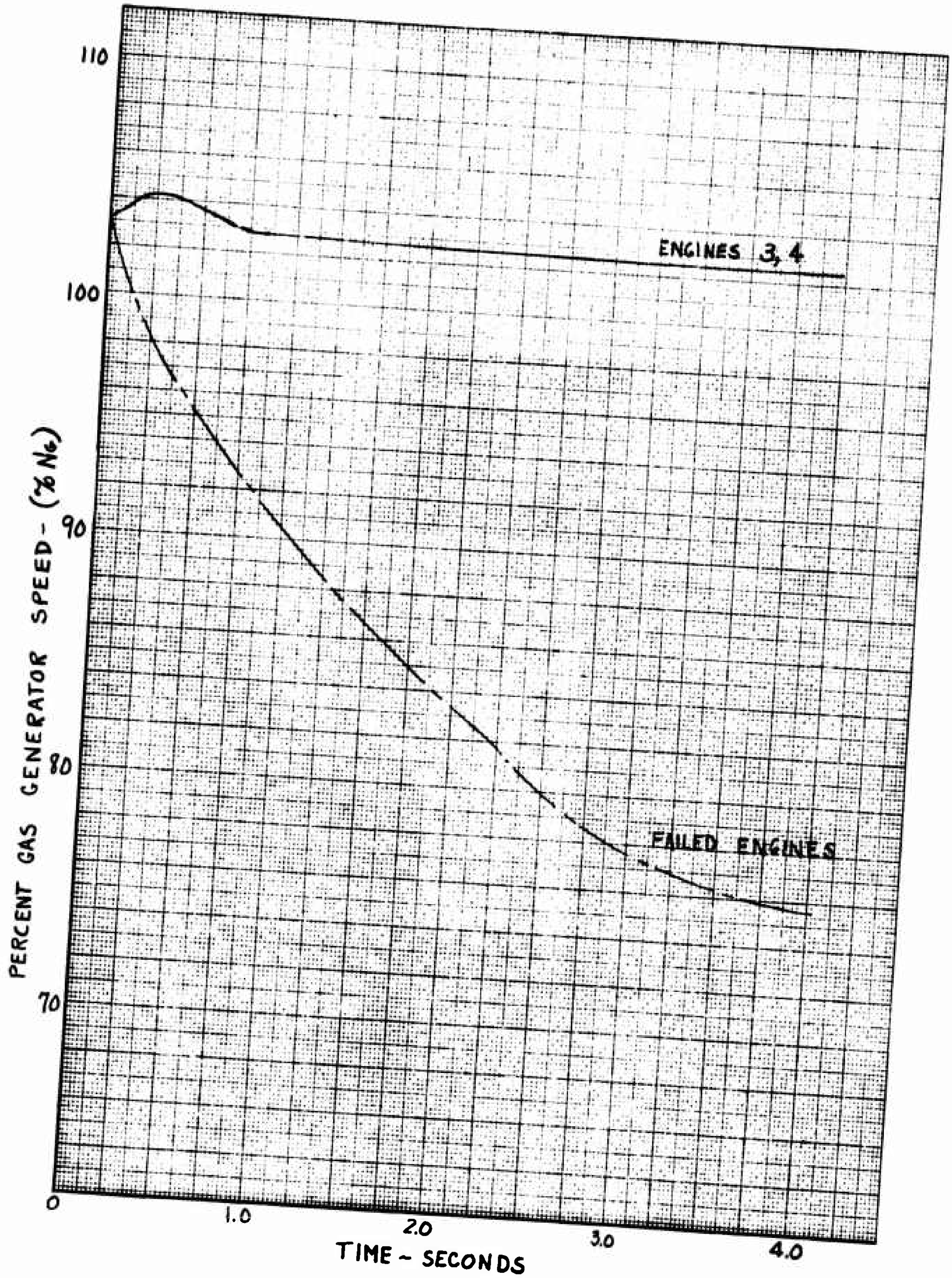


Figure 57. Failure Analysis; Four Engine System; Maximum Load; Two Engines Failed; Divert in 0 Sec: % Ng, vs Time

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APPENDIX I

PROGRAM FOR MONTE CARLO ANALYSIS

The computer program set up for analysis of multiple-engine systems is listed on the following pages, together with a typical output. The program is written in FORTRAN IV and was run on an IBM 7044 computer.

The Monte Carlo technique is used to analyze the steady-state performance of gas generators in multiple-engine systems. A random gas generator is assembled from random selections of component performance. Exhaust conditions are then found by applying partial derivatives from the nominal or average engine base. A multiple-engine system is then assembled from N engines which are adjusted by derivatives to match the common plenum requirements.

Three basic trim methods for maximum power may be investigated: NG trim of all engines to maximum temperature, A8 trim to temperature, and EPR. The power-producing component is a hot gas rotor system.

The total number of engines may be as high as 500, and the number of engines in the multiple system may be one to six. Obviously, the one-engine case is not a multiple system but simulates the production line of individual engines. The capability of handling individual engines can be important for investigating trim methods, or deterioration, on separated engine systems.

Deterioration may be introduced in any component and for any number of engines in the multiple system.

All parameters of interest (temperatures, speed, and power) are printed for each engine and each system. Averages and standard deviations of all parameters are printed for the M systems. Program running time is 12 minutes for 200 engines in four-engine multiple systems, and 8 minutes for the same number of engines in two-engine multiple systems.

```
$IBFTC MAIN    FULIST,REF
      COMMON DUM1,
     1CT5W2,CT4W2,CW5W2,CP5W2,DUMX,
     2CT5EC,CT4EC,CW5EC,CP5EC,DUM2,
     3CT5ET,CT4ET,CW5ET,CP5ET,DUM3,
     4C1,RT4T5,PSO,DUM4,DUM5,
     5T5N,T5MN,T4N,T4MN,W5N,
     6P5N,XNGN,A5N,PS5N,PT7N,
     7DP5NM,FFN,HT7N,HS9IN,HPGN,
     8HPRN,SIHP,SIHPSQ,SING,SINGSQ,
     9RN,RNM
      COMMON      DUM20,
     1XJOA,XJT,XK,XL,   DUM6,
     2RT5NG,RT4NG,RW5NG,RP5NG,DDT4,
     3DNGI,DT5I,DT5MI,DT4I,DT4MI,
     4DW5I,DP5I,W5I,P5I,HPGIT,
     5DIHP,
     6ST5I,ST5ISQ,ST5MI,ST5MIS,ST4I,
     7ST4ISQ,ST4MI,ST4MIS,DP5MI,P5MI,
     8SWI,WPI,SWPI,PT7I,HPRAI,
     9XMAX,DNT,DP,DP1,DP5M
      COMMON     DUM21,
     1SUMW,PW,SUMPW,PT7,TW,
     2SUMTW,TT7,W7,FF7,HT7,
     3H59I,HPG,HPRB,FR,POWR,
     4HPRA,AVIHP,VAIHP,SDIHP,AVING,
     5VAING,SDING,XLOW,XINC,DUM7
      COMMON      DUM22,
     1DW2,DEC,DET,DDT5,DNG,
     2DT5,DT5M,DT4,DT4M,DW5,
     3DP5,T5I,T5MI,T4I,T4MI,
     4XNGI,HPGI,T5,T5M,T4,
     5T4M,W5,P5,XNG,PTM,
     6PSM,HPGAV,SDHPG,HPRBAV,SDHPRB
      COMMON ERR,CTR,DUM25,DUM26,DUM27,
     1 CTRL,DM(4)
      DIMENSION AM(6)
      DIMENSION DW2(6),DEC(6),DET(6),
     1DDT5(6),DNG(6)
      DIMENSION DT5(6),DT5M(6),DT4(6),
     1DT4M(6),DW5(6),DP5(6)
      DIMENSION T5(6),T5M(6),T4(6),T4M(6),
     1W5(6),P5(6),XNG(6),PTM(6),PSM(6)
      DIMENSION T5I(6), T5MI(6), T4I(6), T4MI(6), XNGI(6)
      DIMENSION HPGI(6),DHPGIT(500),DHPRAI(500)
      DIMENSION DHPG(4,500),DHPRB(4,500),DHPRA(4,500),
     1AR(4,500)
      DIMENSION CTR(8),HEAD(12)
      DIMENSION CDHPG(4,110),CDHPRB(4,110),
     1CDHPRA(4,110),CAR(4,110)
      DIMENSION HPGAV(4),SHPGSQ(4),VAHPG(4),
     1SDHPG(4)
      DIMENSION HPRBAV(4),SHPRBS(4),VAHPRB(4),
```

```
     1SDHPRB(4)
      DIMENSION HPRAAV(4),SHPRAS(4),VAHPRA(4),
     1SDHPRA(4)
      DIMENSION ARAV(4),SARSQ(4),VAAR(4),SDAR(4)
      DIMENSION CELLHP(110),CELLAR(110)
   23 DIMENSIONDUM1(1)
      DIMENSION Z(5)
      DIMENSION DT5K(6), DT5MK(6), DT4K(6)
      DIMENSION DT4MK(6),DW5K(6),DP5K(6),DNGK(6)
      DIMENSION XCTR(8)  , YCTR(8)
      DIMENSION CTRL(8)
      DIMENSION DT5MZ(6),DT4MZ(6)
      DIMENSION T5P(6),T5MP(6),T4P(6),T4MP(6),W5P(6),PMP(6),PSMP(6)
      DIMENSION  XNGP(6)
      DIMENSION AVDW2(6),AVDEC(6),AVDET(6),AVDDT5(6),AVDNG(6)
      DIMENSION CTR30(8), CTR31(8), CTR32(8)
      DIMENSION BT5P(6), BT5MP(6), BT4P(6), BT4MP(6),
     1 BW5P(6), BNP(6)
      DIMENSION SHPG(4),SSHPG(4),SHPRB(4),SSHPRB(4),SHPRA(4),SSHPRA(4),
     1SAR(4),SSAR(4)
      DIMENSION ST5(4),SST5(4),ST5M(4),SST5M(4),ST4(4),SST4(4),ST4M(4),
     1SST4M(4),SP5(4),SSP5(4),SNG(4),SSNG(4)
      DIMENSION T5AV(4),SDT5(4),T5MAV(4),SDT5M(4),T4AV(4),SDT4(4),
     1T4MAV(4),SDT4M(4),P5AV(4),SDP5(4),XNGAV(4),SDNGR(4)
      EXTERNAL TZ, THPP7, TFRAR, THPAP
      EXTERNAL TT5NG, TT4NG, TW5NG, TP5NG
      EXTERNAL TT5P5, TT4P5, TW5P5
      QQPTF(X)=(1.33/.33)*(X**(.33/1.33)-1.)/X
      CALL ATHRUZ(Q016HL,6HGOBACK)
      NX = 301
      XCTR(1)=0.
      YCTR(1)=0.
      IF(CTRX-123.456) 5506, 2, 5506
 5506 DO 5000 I=1,NX
 5000 DUM1(I) = 0.
      CTRX = 123.456
      CALL DVCHK(K)
      GO TO 693
 693  READ(5,6010) NDPT
      IF (NDPT) 1694, 1694, 5616
 1694 CALL EXIT
2     CALL IPO(HEAD(1), DUM1(1),NX)
      CALL EXIT
 5616 WRITE(6,5)
    5 FORMAT(1H1)
      N = 6
  3   DC 7 J=1,10
    4 READ(5,8)(HEAD(I),I=1,12)
      WRITE(6,8)(HEAD(I),I=1,12)
    8 FORMAT(12A6)
    7 CONTINUE
      READ(5,10)(T5N,T5MN,T4N,T4MN,W5N,P5N,XNGN,A5N)
   10 FORMAT(8F9.2)
```

```
      WRITE(6,11)(T5N,T5MN,T4N,T4MN,W5N,P5N,XNGN,A5N)
   11 FORMAT(4F9.0,4F9.2)
      READ(5,690) SDW2, SDEC, SDET, SDDT5, SDNG
  690 FORMAT(5F10.3)
      WRITE(6,691)
  691 FORMAT(/52H          SDW2       SDEC       SDET      SDDT5       SDNG)
      WRITE(6,692) SDW2, SDEC, SDET, SDDT5,SDNG
  692 FORMAT(2X,5F10.3)
      READ(5,830)(AVDW2(J),J=1,N)
      READ(5,830)(AVDEC(J),J=1,N)
      READ(5,830)(AVDET(J),J=1,N)
      READ(5,830)(AVDDT5(J),J=1,N)
      READ(5,830)(AVDNG(J),J=1,N)
  830 FORMAT(6F10.3)
      WRITE(6,831)
  831 FORMAT(/52H         AVDW2      AVDEC      AVDET     AVDDT5      AVDNG)
      DO8321 J=1,N
      WRITE(6,832)AVDW2(J),AVDEC(J),AVDET(J),AVDDT5(J),AVDNG(J)
  832 FORMAT(2X,5F10.2)
 8321 CONTINUE
      READ (5,8351) BW2EC
 8351 FORMAT(1F10.4)
      WRITE(6,8352) BW2EC
 8352 FORMAT(2X,6HBW2EC=F10.4)
      READ(5,710)(PSO,RT4T5,C1)
  710 FORMAT(3F10.2)
      WRITE(6,711)(PSO,RT4T5,C1)
  711 FORMAT(/6H  PSO=F7.2,8H  RT4T5=F7.4,5H  C1=F7.2)
      WRITE(6,712)
  712 FORMAT(/17H  MIX PLANE AREAS/)
      READ(5,713)(AM(J),J=1,N)
  713 FORMAT(7F10.2)
      WRITE(6,714)(AM(J),J=1,N)
  714 FORMAT(2X,7F10.2)
      READ(5,720)(CT5W2,CT4W2,CW5W2,CP5W2)
      READ(5,720)(CT5EC,CT4EC,CW5EC,CP5EC)
      READ(5,720)(CT5ET,CT4ET,CW5ET,CP5ET)
  720 FORMAT(4F10.3)
      WRITE(6,715)
  715 FORMAT(/19H  FIXED DERIVATIVES)
      WRITE(6,716)(CT5W2,CT4W2,CW5W2,CP5W2)
  716 FORMAT(/2X,4F10.3)
      WRITE(6,716)(CT5EC,CT4EC,CW5EC,CP5EC)
      WRITE(6,716)(CT5ET,CT4ET,CW5ET,CP5ET)
      READ(5,6010)(INT1)
 6010 FORMAT(1I5)
      READ(5,12)(N,M)
   12 FORMAT(2I5)
      WRITE(6,13)(N,M,INT1)
   13 FORMAT(/4H  N=I3,12H          M=I3,12H          INT=I3)
      READ(5,3650)PMEPR,FREPR
 3650 FORMAT(2F10.3)
      WRITE(6,3651)PMEPR,FREPR
```

```
 3651 FORMAT(/2X,6HPMEPR=F6.3,4X,6HFREPR=F6.3)
      READ(5,3652)FORKR
 3652 FORMAT(F10.0)
      READ(5,3362)JTA,JTD
 3362 FORMAT(2I5)
      WRITE(6,3363)FORKR,JTA,JTD
 3363 FORMAT(/2X,6HFORKR=F3.0,2X,4HJTA=I3,2X,4HJTD=I3)
C     FIND NOMINAL FLOW FUNCTION(FFN)
  550 CALL AOM(W5N,T5N,P5N,A5N,.017,0.,B,PS5N,V,XM)
      Q=QQPTF(P5N/PS5N)*P5N
      DP5NM=C1*Q
  554 PT7N=P5N-DP5NM
      A=N
  556 FFN=(A*W5N*T5N**0.5)/PT7N
C     FIND NOMINAL HPG AND HPR
  560 CALL H(T5N,PT7N,.017,0.,3HAIR,
     16HDISSOC,B,HT7N)
  562 CALL ADPNHN(HT7N,T5N,PT7N,.017,0.,1.0,
     16HFINDHN,6HDISSOC,B,
     2HS9IN,TS9IN,PSO)
  564 HPGN=A*W5N*(HT7N-HS9IN)*778./550.
      PQP=PT7N/PSO
  566 HPRN=A*XLINIT(PQP,0.,THPP7,B)
      WRITE(6,570)(T5N,T5MN,T4N,T4MN,XNGN,
     1PT7N,FFN)
  570 FORMAT(/2X,4F10.0,2F10.2,1F10.3)
      WRITE(6,571)(HPGN,HPRN)
  571 FORMAT(2X,2F10.0)
      IND = 0
      V1=0.
      V2=0.
      V3=0.
      SRNQ=0
      SZ = 0.
      SSZ = 0.
      SGP=0.
      SSGP=0.
      SRBP=0.
      SSRBP=0.
      SRAP=0.
      SSRAP=0.
      ST5P=0.
      SST5P=0.
      ST5MP=0.
      SST5MP=0.
      ST4P=0.
      SST4P=0.
      ST4MP=0.
      SST4MP=0.
      SW5P=0.
      SSW5P=0.
      SNP=0.
      SSNP=0.
```

```
      DO 3550 JT = JTA, 4, JTD
      SHPG(JT)=0.
      SSHPG(JT)=0.
      SHPRB(JT)=0.
      SSHPRB(JT)=0.
      SHPRA(JT)=0.
      SSHPRA(JT)=0.
      SAR(JT)=0.
      SSAR(JT)=0.
      ST5(JT)=0.
      SST5(JT)=0.
      ST5M(JT)=0.
      SST5M(JT)=0.
      ST4(JT)=0.
      SST4(JT)=0.
      ST4M(JT)=0.
      SST4M(JT)=0.
      SP5(JT)=0.
      SSP5(JT)=0.
      SNG(JT)=0.
      SSNG(JT)=0.
 3550 CONTINUE
  650 DO 3000 JOA=1,M
      XJOA=JOA
      WRITE(6,452)JOA
  452 FORMAT(/,2X,23HINDIVIDUAL ENGINES JOA=I3)
C     FIND COMPONENT DEVIATIONS FROM NOMINAL
      DO 42 J=1,N
      DO 698 JR=1,5
      CALL RANBR(IND,RN,INT1,V1,V2,V3)
      A=N
      G=A*5.*XJOA
      RNQ=RN-.5
      SRNQ= SRNQ + RNQ
      AVRNQ = SRNQ/G
      IF (RN- .5) 695, 695, 694
  694 RNM = 1. - RN
      GO TO 696
  695 RNM = RN
  696 Z(JR) = XLINIT(RNM, 0., TZ, B)
      IF (RN - .5)  6971,6971,697
  697 Z(JR) = -Z(JR)
 6971 SZ = SZ + Z(JR)
      SSZ = SSZ + Z(JR) **2
  698 CONTINUE
      AVZ = SZ/G
      SDZ = ((SSZ -(SZ**2)/G)/(G-1.))**.5
   17 DEC(J)=Z(2)*SDEC+AVDEC(J)
      DW2(J)  = BW2EC * DEC(J) + Z(1) * SDW2 + AVDW2(J)
   18 DET(J)=Z(3)*SDET+AVDET(J)
   19 DDT5(J)=Z(4)*SDDT5+AVDDT5(J)
   20 DNG(J)=Z(5)*SDNG+AVDNG(J)
      WRITE(6,6001)Z(1),Z(2),Z(3),Z(4),Z(5)
```

```
6001 FORMAT(2X,5F11.3)
C     FIND PERFORMANCE DEVIATION FROM NOMINAL
   22 RT5NG=XLINIT(DNG(J),0.,TT5NG,B)
   24 RT4NG=XLINIT(DNG(J),0.,TT4NG,B)
   26 RW5NG=XLINIT(DNG(J),0.,TW5NG,B)
   28 RP5NG=XLINIT(DNG(J),0.,TP5NG,B)
   30 DT5(J)=CT5W2*DW2(J)+CT5EC*DEC(J)
     1+CT5ET*DET(J)+RT5NG*DNG(J)
   31 DT5M(J)=DT5(J)+DDT5(J)
   32 DT4(J)=CT4W2*DW2(J)+CT4EC*DEC(J)
     1+CT4ET*DET(J)+RT4NG*DNG(J)
   33 DDT4=RT4T5*DDT5(J)
   34 DT4M(J)=DT4(J)+DDT4
   35 DW5(J)=CW5W2*DW2(J)+CW5EC*DEC(J)
     1+CW5ET*DET(J)+RW5NG*DNG(J)
   40 DP5(J)=CP5W2*DW2(J)+CP5EC*DEC(J)
     1+CP5ET*DET(J)+RP5NG*DNG(J)
      DT5K(J)=DT5(J)
      DT5MK(J)=DT5M(J)
      DT4K(J)=DT4(J)
      DT4MK(J)=DT4M(J)
      DW5K(J)=DW5(J)
      DP5K(J)=DP5(J)
      DNGK(J)=DNG(J)
   42 CONTINUE
      WRITE(6,7008)AVZ,SDZ,AVRNQ
 7008 FORMAT(/2X,3F11.4,/)
C     PREPARATORY INSTRUCTIONS
  748 DNT=0.
      IF(FORKR)750,750,3498
  750 DO 2900 JT=JTA,4,JTD
      XJT=JT
      DO 751 J=1,N
      DT5(J)=DT5K(J)
      DT5M(J)=DT5MK(J)
      DT4(J)=DT4K(J)
      DT4M(J)=DT4MK(J)
      DW5(J)=DW5K(J)
      DP5(J)=DP5K(J)
      DNG(J)=DNGK(J)
  751 CONTINUE
  752 GO TO (44,144,44,144),JT
C     SELECT MAXIMUM DT5M
   44 XMAX=-1.E37
      DO 47 J=1,N
      D=DT5M(J)-XMAX
      IF(D)47,47,45
   45 K=J
      XK=K
      XMAX=DT5M(J)
 47   CONTINUE
      GO TO 250
C     SELECT MAXIMUM DT4M
```

```
  144 XMAX=-1.E37
      DO 147 J=1,N
      D=DT4M(J)-XMAX
      IF(D)147,147,145
  145 K=J
      XK=K
      XMAX=DT4M(J)
 147  CONTINUE
      GO TO 250
  250 GO TO (49,149,251,251),JT
C     INITIAL STEP ON NG RETARD METHOD
  251 DNT=0.
 252  RT5NG = XLINIT(DNT, 0., TT5NG, B)
      RT4NG=XLINIT(DNT,0.,TT4NG,B)
      RW5NG=XLINIT(DNT,0.,TW5NG,B)
      RP5NG = XLINIT(DNT, 0., TP5NG, B)
  253 DO 260 J=1,N
  254 DT5(J)=DT5K(J)+RT5NG*DNT
  255 DT5M(J)=DT5MK(J)+RT5NG*DNT
  256 DT4(J)=DT4K(J)+RT4NG*DNT
  257 DT4M(J)=DT4MK(J)+RT4NG*DNT
  258 DW5(J)=DW5K(J)+RW5NG*DNT
  259 DP5(J)=DP5K(J)+RP5NG*DNT
      DNG(J)=DNGK(J)+DNT
  260 CONTINUE
  261 GO TO (49,149,49,149),JT
C     OPEN A8 METHOD
C     ADJUST MAX DT5M TO ZERO
   49 DP=0.
      HIDT5 = DT5M(K)
      CTR(1)=0.
   50 RT5P5=XLINIT(DP,0.,TT5P5,B)
      XDT5M=RT5P5*DP
      ERR = HIDT5 + XDT5M
   52 CALL QIRE(DP,ERR,0.,-2.,0.,2., .01,20.,CTR,GOWHER)
      IF(GOWHER-Q016HL)54,50,54
   54 GO TO 56
C     ADJUST MAX DT4M TO ZERO
  149 DP=0.
      HIDT4 = DT4M(K)
      CTR(1)=0.
  150 RT4P5=XLINIT(DP,0.,TT4P5,B)
      XDT4M=RT4P5*DP
      ERR = HIDT4 + XDT4M
  152 CALL QIRE(DP,ERR,0.,-2.,0.,2., .01,20.,CTR,GOWHER)
      IF(GOWHER-Q016HL)154,150,154
  154 GO TO 56
C     ADJUST MAX ENGINE
 56   DP1=DP
      CTRL(1)=0.
 59   RT5P5=XLINIT(DP1,0.,TT5P5,B)
   57 RT4P5=XLINIT(DP1,0.,TT4P5,B)
   58 RW5P5=XLINIT(DP1,0.,TW5P5,B)
```

```
 60 DT5Y=DT5(K)+RT5P5*DP1
 61 DT5MZ(K)=DT5M(K)+RT5P5*DP1
 62 DT4Y=DT4(K)+RT4P5*DP1
 63 DT4MZ(K)=DT4M(K)+RT4P5*DP
 64 DW5Y=DW5(K)+RW5P5*DP1
 65 DP5Y=DP5(K)+DP1
 70 T5(K)=T5N*(1.+DT5Y/100.)
 71 T5M(K)=T5MN*(1.+DT5MZ(K)/100.)
 72 T4(K)=T4N*(1.+DT4Y/100.)
 73 T4M(K)=T4MN*(1.+DT4MZ(K)/100.)
 74 W5(K)=W5N*(1.+DW5Y/100.)
 75 P5(K)=P5N*(1.+DP5Y/100.)
 76 XNG(K)=XNGN*(1.+DNG(K)/100.)
C      FIND PS OF MAX ENGINE
C      PRES DROP TO MIX PLANE
80     CALL AOM(W5(K), T5(K), P5(K), A5N, .017, 0., B, PS5, V, XM)
 82 Q=QQPTF(P5(K)/PS5)*P5(K)
    DP5M=C1*Q
 84 PTM(K)=P5(K)-DP5M
C      PS AT MIX PLANE
 86 CALL AOM(W5(K),T5(K),PTM(K),AM(K),.017,0.,B,PSM(K),V,XM)
C      ADJUST OTHER ENGINES TO MATCH PSM
 90 DO 120 J=1,N
    IF(J-K)92,120,92
 92 DP=0.
 93 RT5P5=XLINIT(DP,0.,TT5P5,B)
 94 RW5P5=XLINIT(DP,0.,TW5P5,B)
 95 DP5Z=DP5(J)+DP
 96 DT5Z=DT5(J)+RT5P5*DP
 97 DW5Z=DW5(J)+RW5P5*DP
 98 P5(J)=P5N*(1.+DP5Z/100.)
 99 T5(J)=T5N*(1.+DT5Z/100.)
100 W5(J)=W5N*(1.+DW5Z/100.)
101 CALL AOM(W5(J),T5(J),P5(J),A5N,.017,0.,B,PS5,V,XM)
102 Q=QQPTF(P5(J)/PS5)*P5(J)
    DP5M=C1*Q
103 PTM(J)=P5(J)-DP5M
104 CALL AOM(W5(J),T5(J),PTM(J),AM(J),.017,0.,B,PSM(J),V,XM)
105 ERR=(PSM(J)-PSM(K))
106 CALL QIRE(DP,ERR,0.,-2.,0.,2.,  .01,20.,CTR,GOWHER)
107 IF(GOWHER-Q016HL)110,93,110
110 RT4P5=XLINIT(DP,0.,TT4P5,B)
111 DT5MZ(J)=DT5M(J)+RT5P5*DP
112 DT4Z=DT4(J)+RT4P5*DP
113 DT4MZ(J)=DT4M(J)+RT4P5*DP
114 DNGZ=DNG(J)
115 T5M(J)=T5MN*(1.+DT5MZ(J)/100.)
116 T4(J)=T4N*(1.+DT4Z/100.)
117 T4M(J)=T4MN*(1.+DT4MZ(J)/100.)
118 XNG(J)=XNGN*(1.+DNGZ/100.)
120 CONTINUE
C      CHECK THAT NO TM IS OVER TMN
121 GO TO (122,200,122,200),JT
```

```
C       SELECT MAX T5M
   122 XMAX=-1.E37
       DO 125 J=1,N
       D=DT5MZ(J)-XMAX
       IF(D)125,125,123
   123 L=J
       XMAX = DT5MZ(J)
   125 CONTINUE
C       COMPARE MAX T5 TO NOM
       XL=L
       IF (CTRL(1)-.5)2126,127,127
  2126 IF(DT5MZ(L)-.02)129,129,126
   126 CHG=.7*DT5MZ(L)*2.
   127 CALL QIRE(DP1,DT5MZ(L),0.,-CHG,0.,CHG,.02,20.,CTRL,GOWHER)
       IF (GOWHER-Q016HL)129,59,129
C       SELECT MAX T4M
   200 XMAX=-1.E37
       DO 205 J=1,N
       D=DT4MZ(J)-XMAX
       IF(D)205,205,203
   203 L=J
       XMAX = DT4MZ(J)
   205 CONTINUE
C       COMPARE MAX T4M TO NOM
       XL=L
       IF (CTRL(1)-.5)2206,207,207
  2206 IF(DT4MZ(L)-.02)129,129,206
   206 CHG=.7*DT4MZ(L)*2.
   207 CALL QIRE(DP1,DT4MZ(L),0.,-CHG,0.,CHG,.02,20.,CTRL,GOWHER)
       IF (GOWHER-Q016HL)129,59,129
C       FLOW WEIGHT PRES
   129 SUMW=0.
       SUMPW=0.
   130 DO 134 J=1,N
       SUMW=SUMW+W5(J)
       PW=PTM(J)*W5(J)
   134 SUMPW=SUMPW+PW
   136 PT7=SUMPW/SUMW
C       FLOW WEIGHT TEMP
       SUMTW=0.
   138 DO 140 J=1,N
       TW=T5(J)*W5(J)
       SUMTW=SUMTW+TW
   139 TT7=SUMTW/SUMW
   140 W7=SUMW
   141 FF7=W7*TT7**0.5/PT7
   142 GO TO (156,156,280,280),JT
C       CHANGE NG TO MATCH FF IF IN NG LOOP
   280 ERR=(FF7-FFN)
   282 CALL QIRE(DNT,ERR,0.,-2.,0.,2.,  .01,20.,XCTR,GOWHER)
  283  IF (GOWHER - Q016HL) 284, 252, 284
   284 GO TO 156
C       CALCULATE GAS HP
```

```
  156 CALL H(TT7,PT7,.017,0.,3HAIR,6HDISSOC,B,HT7)
  158 CALL ADPNHN(HT7,TT7,PT7,.017,0.,1.0,6HFINDHN,6HDISSOC,B,HS9I,TS9I,
     1PSO)
      HPG=W7*(HT7-HS9I)*778./550.
  160 DHPG(JT,JOA)=(HPG-HPGN)*100./HPGN
C     CALCULATE ROTOR PERFORMANCE
  300 A=N
      PQP=PT7/PSO
  301 HPRB=A*XLINIT(PQP,0.,THPP7,B)
  302 DHPRB(JT,JOA)=(HPRB-HPRN)*100./HPRN
  303 FR=FF7/FFN
  304 AR(JT,JOA)=XLINIT(FR,0.,TFRAR,B)
  305 POWR=XLINIT(AR(JT,JOA),PQP,THPAP,B)
  306 HPRA=HPRB*POWR
  307 DHPRA(JT,JOA)=(HPRA-HPRN)*100./HPRN
      T=A*XJOA
      SHPG(JT)=SHPG(JT)+DHPG(JT,JOA)
      SSHPG(JT)=SSHPG(JT)+DHPG(JT,JOA)**2
      HPGAV(JT)=SHPG(JT)/XJOA
      SHPRB(JT)=SHPRB(JT)+DHPRB(JT,JOA)
      SSHPRB(JT)=SSHPRB(JT)+DHPRB(JT,JOA)**2
      HPRBAV(JT)=SHPRB(JT)/XJOA
      SHPRA(JT)=SHPRA(JT)+DHPRA(JT,JOA)
      SSHPRA(JT)=SSHPRA(JT)+DHPRA(JT,JOA)**2
      HPRAAV(JT)=SHPRA(JT)/XJOA
      SAR(JT)=SAR(JT)+AR(JT,JOA)
      SSAR(JT)=SSAR(JT)+AR(JT,JOA)**2
      ARAV(JT)=SAR(JT)/XJOA
      DO 3340 J=1,N
      BT5=(T5(J)-T5N)*100./T5N
      ST5(JT)=ST5(JT)+BT5
      SST5(JT)=SST5(JT)+BT5**2
      BT5M=(T5M(J)-T5MN)*100./T5MN
      ST5M(JT)=ST5M(JT)+BT5M
      SST5M(JT)=SST5M(JT)+BT5M**2
      BT4=(T4(J)-T4N)*100./T4N
      ST4(JT)=ST4(JT)+BT4
      SST4(JT)=SST4(JT)+BT4**2
      BT4M=(T4M(J)-T4MN)*100./T4MN
      ST4M(JT)=ST4M(JT)+BT4M
      SST4M(JT)=SST4M(JT)+BT4M**2
      BP5=(P5(J)-P5N)*100./P5N
      SP5(JT)=SP5(JT)+BP5
      SSP5(JT)=SSP5(JT)+BP5**2
      BN=XNG(J)-XNGN
      SNG(JT)=SNG(JT)+BN
      SSNG(JT)=SSNG(JT)+BN**2
 3340 CONTINUE
      T5AV(JT)=T5N*(1.+(ST5(JT)/T)/100.)
      T5MAV(JT)=T5MN*(1.+(ST5M(JT)/T)/100.)
      T4AV(JT)=T4N*(1.+(ST4(JT)/T)/100.)
      T4MAV(JT)=T4MN*(1.+(ST4M(JT)/T)/100.)
      P5AV(JT)=P5N*(1.+(SP5(JT)/T)/100.)
```

```
      XNGAV(JT)=XNGN+SNG(JT)/T
      IF(JOA-1)3492,3492,3491
 3491 SDHPG(JT)=((SSHPG(JT)-(SHPG(JT)**2)/XJOA)/  (XJOA-1.)) **.5
      SDHPRB(JT)=((SSHPRB(JT)-(SHPRB(JT)**2)/XJOA)  /(XJOA-1.))**.5
      SDHPRA(JT)=((SSHPRA(JT)-(SHPRA(JT)**2)/XJOA)/(XJOA-1.)) **.5
      SDAR(JT)=((SSAR(JT)-(SAR(JT)**2)/XJOA)  /(XJOA-1.)) **.5
      SDT=((SST5(JT)-(ST5(JT)**2)/T)/(T-1.))**.5
      SDT5(JT)=SDT*T5N/100.
      SDTM=((SST5M(JT)-(ST5M(JT)**2)/T)/(T-1.))**.5
      SDT5M(JT)=SDTM*T5MN/100.
      SDF=((SST4(JT)-(ST4(JT)**2)/T)/(T-1.))**.5
      SDT4(JT)=SDF*T4N/100.
      SDFM=((SST4M(JT)-(ST4M(JT)**2)/T)/(T-1.))**.5
      SDT4M(JT)=SDFM*T4MN/100.
      SDP=((SSP5(JT)-(SP5(JT)**2)/T)/(T-1.))**.5
      SDP5(JT)=SDP*P5N/100.
      SDNGR(JT)=((SSNG(JT)-(SNG(JT)**2)/T)/(T-1.))**.5
 3492 GO TO (350,360,370,380),JT
  350 WRITE(6,351)JOA
  351 FORMAT(/,2X,21HOPEN A8,HOLD T5M JOA=I3)
  385 WRITE(6,352)(T5(J),T5M(J),T4(J),T4M(J),XNG(J),J=1,N)
  352 FORMAT(2X,4F11.0,F11.2)
      WRITE(6,353)(DHPG(JT,JOA),DHPRB(JT,JOA),DHPRA(JT,JOA),AR(JT,JOA))
  353 FORMAT(/2X,4F11.3,/)
      WRITE(6,3520)T5AV(JT),T5MAV(JT),T4AV(JT),T4MAV(JT),P5AV(JT),
     1XNGAV(JT)
 3520 FORMAT(2X, 4F11.0,2F11.2)
      WRITE(6,3521)SDT5(JT),SDT5M(JT),SDT4(JT),SDT4M(JT),SDP5(JT),
     1SDNGR(JT)
 3521 FORMAT(2X,6F11.3)
      WRITE(6,3522)HPGAV(JT),HPRBAV(JT),HPRAAV(JT),ARAV(JT)
 3522 FORMAT(/2X,4F11.3)
      WRITE(6,3523)SDHPG(JT),SDHPRB(JT),SDHPRA(JT),SDAR(JT)
 3523 FORMAT(2X,4F11.3)
      GO TO 2900
  360 WRITE(6,361)JOA
  361 FORMAT(/,2X,21HOPEN A8,HOLD T4M JOA=I3)
      GC TO 385
  370 WRITE(6,371)JOA
  371 FORMAT(/,2X,23HRETARD NG,HOLD T5M JOA=I3)
      GO TO 385
  380 WRITE(6,381)JOA
  381 FORMAT(/,2X,23HRETARD NG,HOLD T4M JOA=I3)
      GO TO 385
 2900 CONTINUE
C     FIND DISTRIBUTION OF TEMP AT PT7 AND FFN
 3498 IF(FORKR)3000,3499,3499
 3499 DNT2=0.
 3500 RT5NG=XLINIT(DNT2,0.,TT5NG,B)
      RT4NG=XLINIT(DNT2,0.,TT4NG,B)
      RW5NG=XLINIT(DNT2,0.,TW5NG,B)
      RP5NG=XLINIT(DNT2,0.,TP5NG,B)
      DP4=0.
```

```
 3509 CONTINUE
      DP3=0.
      DO3601J=1,N
 3510 DP2=DP3+DP4
      RT5P5=XLINIT(DP2,0.,TT5P5,B)
      RT4P5=XLINIT(DP2,0.,TT4P5,B)
      RW5P5=XLINIT(DP2,0.,TW5P5,B)
      BT5P(J) = DT5K(J) + RT5P5 * DP2 + RT5NG * DNT2
      T5P(J) = T5N * (1. + BT5P(J)/100.)
      BT5MP(J) = DT5MK(J) + RT5P5 * DP2 + RT5NG * DNT2
      T5MP(J) = T5MN * (1. + BT5MP(J)/100.)
      BT4P(J) = DT4K(J) + RT4P5 * DP2 + RT4NG * DNT2
      T4P(J) = T4N * (1. + BT4P(J)/100.)
      BT4MP(J) = DT4MK(J) + RT4P5 * DP2 + RT4NG * DNT2
      T4MP(J) = T4MN * (1. + BT4MP(J)/100.)
      BW5P(J) = DW5K(J) + RW5P5 * DP2 + RW5NG * DNT2
      W5P(J) = W5N * (1. + BW5P(J)/100.)
      BNP(J) = DNGK(J) + DNT2
      XNGP(J) = XNGN * (1. + BNP(J)/100.)
      P5P=P5N*(1.+(DP5K(J)+DP2+RP5NG*DNT2)/100.)
      CALL AOM(W5P(J),T5P(J),P5P,A5N,.017,0.,B,PS5P,V,XM)
      Q=QQPTF(P5P/PS5P)*P5P
      DP57=C1*Q
      PMP(J)=P5P-DP57
      CALL AOM(W5P(J),T5P(J),PMP(J),A5N,.017,0.,B,PSMP(J),V,XM)
      ERR=PSMP(J)-PSMP(1)
      CALL QIRE(DP3,ERR,0.,-2.,0.,2.,.01,20.,CTR30,GOWHER)
      IF(GOWHER-Q016HL)3601,3510,3601
 3601 CONTINUE
C     FLOW WEIGHT PRESSURE AND TEMP
      SWP=0.
      SWPPM=0.
      SWPTP=0.
      DO3610J=1,N
      SWP=SWP+W5P(J)
      WPPM=W5P(J)*PMP(J)
      SWPPM=SWPPM+WPPM
      P7P=SWPPM/SWP
      WPTP=W5P(J)*T5P(J)
      SWPTP=SWPTP+WPTP
      T7P=SWPTP/SWP
      W7P=SWP
 3610 CONTINUE
C     COMPARE PRESSURE
      ERR=P7P-(PT7N*PMEPR)
 3619 CALL QIRE(DP4,ERR,0.,-2.,0.,2.,.01,20.,CTR31,GOWHER)
      IF(GOWHER-Q016HL)3620,3509,3620
C     COMPARE FLOW FUNCTION
 3620 FF7P=W7P*T7P**.5/P7P
      ERR=FF7P-(FFN*FREPR)
      CALL QIRE(DNT2,ERR,0.,-2.,0.,2.,.01,20.,CTR32,GOWHER)
      IF(GOWHER-Q016HL)3600,3500,3600
 3600 A=N
```

```
      T=A*XJOA
      DO 3800 J=1,N
      ST5P=ST5P+BT5P(J)
      SST5P=SST5P+BT5P(J)**2
      AVT5P=T5N*(1.+(ST5P/T)/100.)
      ST5MP=ST5MP+BT5MP(J)
      SST5MP=SST5MP+BT5MP(J)**2
      AVT5MP=T5MN*(1.+(ST5MP/T)/100.)
      ST4P=ST4P+BT4P(J)
      SST4P=SST4P+BT4P(J)**2
      AVT4P=T4N*(1.+(ST4P/T)/100.)
      ST4MP=ST4MP+BT4MP(J)
      SST4MP=SST4MP+BT4MP(J)**2
      AVT4MP=T4MN*(1.+(ST4MP/T)/100.)
      SW5P=SW5P+BW5P(J)
      SSW5P=SSW5P+BW5P(J)**2
      AVW5P=W5N*(1.+(SW5P/T)/100.)
      SNP=SNP+BNP(J)
      SSNP=SSNP+BNP(J)**2
      AVNP=XNGN*(1.+(SNP/T)/100.)
      IF (JOA -1)  3800, 3800, 3615
 3615 SDPCT=((SST5P-(ST5P**2)/T)/(T-1.))**.5
      SDT5P=SDPCT*T5N/100.
      SDPCT=((SST5MP-(ST5MP**2)/T)/(T-1.))**.5
      SDT5MP=SDPCT*T5MN/100.
      SDPCT=((SST4P-(ST4P**2)/T)/(T-1.))**.5
      SDT4P=SDPCT*T4N/100.
      SDPCT=((SST4MP-(ST4MP**2)/T)/(T-1.))**.5
      SDT4MP=SDPCT*T4MN/100.
      SDPCT=((SSW5P-(SW5P**2)/T)/(T-1.))**.5
      SDW5P=SDPCT*W5N/100.
      SDNP=((SSNP-(SNP**2)/T)/(T-1.))**.5
 3800 CONTINUE
C     CALCULATE OUTPUT
 3630 CALL H(T7P,P7P,.017,0.,3HAIR,6HDISSOC,B,H7P)
      CALL ADPNHN(H7P,T7P,P7P,.017,0.,1.0,6HFINDHN,6HDISSOC,B,HS9IP,
     1TS9IP,PS0)
      HPGP=W7P*(H7P-HS9IP)*778./550.
 3631 DHPGP=(HPGP-HPGN)*100./HPGN
      A=N
      PQP=P7P/PS0
      HPRBP=A*XLINIT(PQP,0.,THPP7,B)
 3632 DHPRBP=(HPRBP-HPRN)*100./HPRN
      FRP=FF7P/FFN
      AREPR=XLINIT(FRP,0.,TFRAR,B)
      POWRR=XLINIT(AREPR,PQP,THPAP,B)
      HPRAP=HPRBP*POWRR
 3633 DHPRAP=(HPRAP-HPRN)*100./HPRN
      SGP=SGP+DHPGP
      SSGP=SSGP+DHPGP**2
      AVGP=SGP/XJOA
      SRBP=SRBP+DHPRBP
      SSRBP=SSRBP+DHPRBP**2
```

```
      AVRBP=SRBP/XJOA
      SRAP=SRAP+DHPRAP
      SSRAP=SSRAP+DHPRAP**2
      AVRAP=SRAP/XJOA
      IF (JOA - 1) 3639, 3639, 3634
 3634 SDGP=((SSGP-(SGP**2)/XJOA)/(XJOA-1.))**.5
      SDRBP=((SSRBP-(SRBP**2)/XJOA)/(XJOA-1.))**.5
      SDRAP=((SSRAP-(SRAP**2)/XJOA)/(XJOA-1.))**.5
 3639 WRITE(6,3640)JOA
 3640 FORMAT(/,2X,15HEPR METHOD JOA=I3)
      WRITE(6,3641)(T5P(J),T5MP(J),T4P(J),T4MP(J),XNGP(J),J=1,N)
 3641 FORMAT(2X,4F11.0,F11.2)
      WRITE(6,3644)(DHPGP,DHPRBP,DHPRAP)
 3644 FORMAT(/2X,3F11.3)
      WRITE(6,3801)AVT5P,AVT5MP,AVT4P,AVT4MP,AVW5P,AVNP
 3801 FORMAT(/2X,4F11.0,2F11.2)
      WRITE(6,3802)SDT5P,SDT5MP,SDT4P,SDT4MP,SDW5P,SDNP
 3802 FORMAT(2X,6F11.3)
      WRITE(6,3642)AVGP,AVRBP,AVRAP,AREPR
 3642 FORMAT(/2X,4F11.3)
      WRITE(6,3643)SDGP,SDRBP,SDRAP
 3643 FORMAT(2X,3F11.3)
 3000 CONTINUE
      IF (FORKR) 3001, 3001, 693
C     CALCULATE DATA FOR PLOTTING
 3001 DO 848 JT = JTA, 4, JTD
      DO 846 JF=1,110
      CDHPG(JT,JF)=0.
      CDHPRB(JT,JF)=0.
      CDHPRA(JT,JF)=0.
      CAR(JT,JF)=0.
  846 CONTINUE
  848 CONTINUE
  850 DO 868 JT = JTA, 4, JTD
  860 DO 868 JOA=1,M
      XLOW=-15.2
      XINC=.4
  861 DO 867 JF=1,110
  862 IF(DHPG(JT,JOA)-XLOW)864,866,866
  864 CDHPG(JT,JF)=CDHPG(JT,JF)+1.
  865 GO TO 868
  866 XLOW=XLOW+XINC
  867 CONTINUE
  868 CONTINUE
      DO 869 JF=1,110
      XJF = JF
      CELLHP(JF) =-15.2 +(XJF - 1.5) * XINC
  869 CONTINUE
  870 DO 878 JT = JTA, 4, JTD
  871 DO 878 JOA=1,M
      XLOW = -15.2
      DO 877 JF=1,110
      IF(DHPRB(JT,JOA)-XLOW)874,876,876
```

```
 874 CDHPRB(JT,JF)=CDHPRB(JT,JF)+1.
     GO TO 878
 876 XLOW=XLOW+XINC
 877 CONTINUE
 878 CONTINUE
 880 DO 888 JT = JTA, 4, JTD
881  DO 888 JOA=1,M
     XLOW = -15.2
     DO 887 JF=1,110
     IF(DHPRA(JT,JOA)-XLOW)884,886,886
 884 CDHPRA(JT,JF)=CDHPRA(JT,JF)+1.
     GO TO 888
 886 XLOW=XLOW+XINC
 887 CONTINUE
 888 CONTINUE
 890 DO 898 JT = JTA, 4, JTD
891  DO 898 JOA=1,M
     XLOW=.961
     XINC=.002
     DO 897 JF=1,110
     IF(AR(JT,JOA)-XLOW)894,896,896
 894 CAR(JT,JF)=CAR(JT,JF)+1.
     GO TO 898
 896 XLOW=XLOW+XINC
 897 CONTINUE
 898 CONTINUE
     DO 960 JF = 1,110
     XJF=JF
     CELLAR(JF) = .961+ (XJF-1.5)*XINC
960  CONTINUE
 920 WRITE(6,921)
 921 FORMAT(///,2X,13HDISTRIBUTIONS)
     DO 950 JT = JTA, 4, JTD
     GO TO (922, 924, 926, 928),JT
 922 WRITE(6,923)
 923 FORMAT(//,2X,17HOPEN A8, HOLD T5M)
     GO TO 940
 924 WRITE(6,925)
 925 FORMAT(//,2X,17HOPEN A8, HOLD T4M)
     GO TO 940
 926 WRITE(6,927)
 927 FORMAT(//,2X,19HRETARD NG, HOLD T5M)
     GO TO 940
 928 WRITE(6,929)
 929 FORMAT(//,2X,19HRETARD NG, HOLD T4M)
     GO TO 940
 940 WRITE(6,941)
 941 FORMAT(/2X,65H  PCTDHP    CDHPG   CDHPRB   CDHPRA
    1AR         CAR/)
 942 WRITE(6,943)(CELLHP(JF),CDHPG(JT,JF),CDHPRB(JT,JF),
    1CDHPRA(JT,JF),CELLAR(JF),CAR(JT,JF),JF=1,110)
 943 FORMAT(2X,1F8.2,3F8.0,1F24.3,1F8.0)
 950 CONTINUE
```

TYPICAL OUTPUT

T64 AVLABS STUDY

```
    PREDICTION OF MAX POWER WITH FOUR TRIM PROCEDURES
          1  OPEN A8, HOLD T5M
          2  OPEN A8, HOLD T4M
INPUT     3  RETARD NG, HOLD T5M
DATA      4  RETARD NG, HOLD T4M
                                                  NOMINAL ENGINE DESCRIPTION
     T5N      T5MN      T4N      T4MN      W5N      P5N      XNGN      A5N

   1611.     1611.     2227.     2227.     26.67    41.95   104.14    85.00
          WZ         ηc        ηT       ΔT5       NG
      SDW2      SDEC      SDET      SDDT5      SDNG
      1.000     0.400     0.330     0.600     0.200        COMPONENT
                                                          VARIATION
      AVDW2     AVDEC     AVDET     AVDDT5     AVDNG       AND
       0.00      0.00      0.00      0.00      0.00       AVERAGE
       0.00      0.00      0.00      0.00      0.00       DEVIATIONS
       0.00      0.00      0.00      0.00      0.00
       0.00      0.00      0.00      0.00      0.00
       0.00      0.00      0.00      0.00      0.00
       0.00      0.00      0.00      0.00      0.00
 BW2EC=     0.9170

 PSO=  14.70  RT4T5= 0.7240  C1=   0.00

 MIX PLANE AREAS

      85.00     85.00     85.00     85.00     -0.00     -0.00

 FIXED DERIVATIVES

      0.700     0.670     0.890     1.210

     -1.370    -1.290     0.030    -0.660

     -1.940    -1.420     0.030    -0.960

 N=  2          M=100         INT=  9

 PMEPR= 1.000     FREPR= 1.000

 FORKR= 0.   JTA=  1   JTD=  2

      1611.     1611.     2227.     2227.    104.14     41.95     51.035
      7680.     6525.

 INDIVIDUAL ENGINES JOA=  1
       2.502     -0.712     0.463     -0.166      1.510
       1.135     -0.976     0.522      0.308     -1.699

      0.2888     1.2451    0.0679


 OPEN A8,HOLD T5M  JOA=  1
       1606.      1604.     2234.      2271.     104.45
       1608.      1611.     2226.      2229.     103.79

       0.851     -0.350     0.643      1.020

       1607.      1608.     2230.      2250.      41.87     104.12
      12.354     13.170    13.751     16.998      0.456      0.217
```

0.851 -0.350 0.643 1.020
1.774 1.925 1.619 0.013

RETARD NG,HOLD T5M JOA= 1

1606. 1604. 2226. 2263. 103.50
1608. 1611. 2219. 2222. 102.83

-1.096 -0.939 -0.936 1.000

1607. 1608. 2222. 2243. 41.73 103.16
12.331 13.150 16.017 18.828 0.516 0.590

-1.096 -0.939 -0.936 1.000
2.465 2.184 2.184 0.001

EPR METHOD JOA= 1

1611. 1609. 2232. 2231. 103.70
1613. 1616. 2226. 2229. 103.03

0.038 -0.000 0.005

1612. 1613. 2229. 2230. 26.66 103.36
10.278 14.974 11.905 15.993 0.203 0.426

0.038 -0.000 0.005 1.000
0.220 0.004 0.004

INDIVIDUAL ENGINES JOA= 2 ← SYSTEM NUMBER

1.488 -0.233 -1.103 -0.107 0.241 } Z VALUES FOR EACH ENGINE
-0.840 -0.811 0.639 -0.388 0.400

0.1088 1.0308 0.0179
CUM. AVG Z CUM SD Z CUM AVG RANDOM NUMBER

OPEN AB,HOLD T5M JOA= 2 ← TRIM METHOD

1612. T5 1611. T5M 2234. T4 2233. T4M 104.19 NG } INDIVIDUAL ENGINE VALUES
1605. 1601. 2220. 2216. 104.22

HPG HPRB HPRA AB/AB nom
-0.437 -1.044 -0.517 1.011 } SYSTEM VALUES (% diff from nom)

1608. T5 1607. T5M 2228. T4 2237. T4M 41.78 NG 104.16 } CUM. AVG & STD DEV.
3.174 4.990 6.691 23.655 0.135 0.278

HPG HPRB HPRA AB/AB nom
0.207 -0.697 0.063 1.015 } CUM AVG & STD DEV.
0.911 0.490 0.820 0.007

RETARD NG,HOLD T5M JOA= 2

1612. 1611. 2230. 2229. 103.67
1605. 1601. 2216. 2212. 103.70

-1.438 -1.329 -1.325 1.000

1608. 1607. 2222. 2231. 41.68 103.42
3.189 4.979 6.282 22.408 0.109 0.409

-1.267 -1.134 -1.131 1.000
0.242 0.276 0.275 0.000

EPR METHOD JOA= 2

1619. 1618. 2239. 2238. 103.97
1612. 1609. 2226. 2222. 104.01

APPENDIX II

DYNASAR PROGRAM

The DYNASAR listing presented in this appendix is identical to the functional block diagram for the system as shown in Figures 12 through 17. Each operation in the listing is numbered with the same number used to represent that same operation in the block diagrams. The number of the operation is located immediately following the term (= BOX) in the listing. All other information required to fully describe the operation is listed on the same line as the operation number and on those lines immediately preceding, which do not contain the number of another operation.

The number following the operation number represents the type of operation to be performed; for example,

Type 7 is a first-order differential equation.
Type 9 is a summation.
Type 10 is a maximum or minimum limit.
Type 11 is a multiplication.
Type 13 is a division.
Type 14 is a two-dimensional table y = f (x).
Type 22 selects the maximum or minimum limit.

*Some examples from the printout follow:

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(a) = Box, 142, 11, 141, 5, 1.0, 1.0,
is equivalent to Box 142 = (Output of Box 141) × 1.0 × (Output of Box 5) × 1.0

(b) = Box, 134, 13, 133, 9, 1.0, 1.0
is equivalent to Box 134 - (Output of Box 133) × 1.0/ (Output of Box 9) × 1.0

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(c) = Box, 107, 7, 106, 1.0, 1.0, 0.378, , , 6.65
is equivalent to Box 107 = $\dfrac{\text{(Output of Box 106)} \times 1.0}{0.0378\ S \times 1.0}$

NOTE: 6.65 is an estimated initial value of the output used to save computation time.

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(d) = Box, 110, 14, 109, 15, 3.
Box 110 is a function of the output of Box 109. The table for this is given immediately preceding the operation; viz.,

*The listing shown in this appendix is the case of one engine failed in the four-engine system, with the diverter valve operating instantaneously. This example was chosen since it demonstrates the operation of the complete system.

Output of 109 (XT)	Output of 110 (YT)
70	9.80
75	9.62
80	9.45
85	9.35
etc.	etc.

Note: Box 210 is the same function of Box 209.

```
*     JOB   3026900800  LYNN G.E.  MOZZICATO     71090005  EXT. 3935
*     XEQ
=BOX,0,
5NAME,10, MOZZICATO   DATE FEB 12   CHARGE 71090005
5ADDRESS,10, T64 CONTROLS   BLDG 2-40   EXT 3935
5IDENT,10, ONE ENG FAILED   DIVERT 0 SEC
5IDENA,10, .5 SEC DIVERTER   .25 SEC TIP NOZZLE
3EXTRA,5.0,.05,
3EXTRA,5=, ,0, ,100,
4NBOX,2=,1, ,121, ,132, ,134, ,135, ,136, ,142, ,
 2, ,221, ,232, ,234, ,235, ,236, ,242, ,
 3, ,321, ,332, ,334, ,335, ,336, ,342, ,
 4, ,421, ,432, ,434, ,435, ,436, ,442, ,
 509, ,516, ,929, ,930, ,701, ,702, ,911, ,
 610, ,607, ,603, ,608, ,604, ,114, ,214, ,
 613, ,160, ,260, ,15, ,170, ,175, ,173, ,
=BOX,-88,
4JUMP,4=,1,
3EMAX,3=, ,200,
3EMAX,5/-4,1/-3,
3PRINTC,10/-2,PRINTD,1/3,
3EMAX,9=, ,PRINTE,1,
=BOX,-99,
=BOX,142,11,141,5,1.0,1.0,
=BOX,242,11,241,5,1.0,1.0,
=BOX,342,11,341,5,1.0,1.0,
=BOX,442,11,441,5,1.0,1.0,
=BOX,132,11,125,8,1.0,1.0,
=BOX,232,11,225,8,1.0,1.0,
=BOX,332,11,325,8,1.0,1.0,
=BOX,432,11,425,8,1.0,1.0,
=BOX,133,11,124,5,1.0,1.0,
=BOX,233,11,224,5,1.0,1.0,
=BOX,333,11,324,5,1.0,1.0,
=BOX,433,11,424,5,1.0,1.0,
=BOX,134,13,133,9,1.0,1.0,
=BOX,234,13,233,9,1.0,1.0,
=BOX,334,13,333,9,1.0,1.0,
=BOX,434,13,433,9,1.0,1.0,
=BOX,135,11,130,5,1.0,1.0,
=BOX,235,11,230,5,1.0,1.0,
=BOX,335,11,330,5,1.0,1.0,
=BOX,435,11,430,5,1.0,1.0,
=BOX,136,11,108,10,1.0,1.0,
=BOX,236,11,208,10,1.0,1.0,
=BOX,336,11,308,10,1.0,1.0,
=BOX,436,11,408,10,1.0,1.0,
=BOX,516,11,512,5,1.0,1.0,
=BOX,517,11,506,5,1.0,1.0,
=BOX,518,13,517,9,1.0,1.0,
5IDEN,10, PLA MOTION
3XT,0,.999,1.0,5,
```

```
3YT,100,100,30,30,
=BOX,1,5, ,4,2,
5IDEN,10, PLA MOTION ENG TWO
3XT,0,.999,1.0,5,
3YT,100,100,100,100,
=BOX,2,5, ,4,2,
=BOX,3,1, , ,100,
=BOX,4,1, , ,100,
=BOX,5,1, , ,1.0,
=BOX,7,1, , ,1.0,
=BOX,8,1, , ,1.0,
=BOX,9,1, , ,1.0,
=BOX,10,1, , ,1.0,
=BOX,11,1, , ,3.5,
=BOX,12,1, , ,3.5,
=BOX,13,1, , ,3.5,
=BOX,14,1, , ,3.5,
=BOX,15,9,7,-735,-736,
=BOX,103,7,121,1.0,1.0,.089, , ,78,
=BOX,203,7,221,1.0,1.0,.089, , ,78,
=BOX,303,7,321,1.0,1.0,.089, , ,78,
=BOX,403,7,421,1.0,1.0,.089, , ,78,
=BOX,104,11,103,103,.00384,1.0,
=BOX,204,11,203,203,.00384,1.0,
=BOX,304,11,303,303,.00384,1.0,
=BOX,404,11,403,403,.00384,1.0,
=BOX,105,22,-1,101,111,1.0,1.0,
=BOX,205,22,-1,201,211,1.0,1.0,
=BOX,305,22,-1,301,311,1.0,1.0,
=BOX,405,22,-1,401,411,1.0,1.0,
=BOX,106,22,1,11,105,1.0,1.0,
=BOX,206,22,1,12,205,1.0,1.0,
=BOX,306,22,1,13,305,1.0,1.0,
=BOX,406,22,1,14,405,1.0,1.0,
=BOX,107,7,106,1.0,1.0,.0378, , ,6.65,
=BOX,207,7,206,1.0,1.0,.0378, , ,6.65,
=BOX,307,7,306,1.0,1.0,.0378, , ,6.65,
=BOX,407,7,406,1.0,1.0,.0378, , ,6.65,
=BOX,109,13,103,9,1.0,1.0,
=BOX,209,13,203,9,1.0,1.0,
=BOX,309,13,303,9,1.0,1.0,
=BOX,409,13,403,9,1.0,1.0,
=BOX,111,11,110,10,1.0,1.0,
=BOX,211,11,210,10,1.0,1.0,
=BOX,311,11,310,10,1.0,1.0,
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5IDEN,10,NG CONTROL RATE
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=BOX,703,14,707,
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=BOX,907,9,903,-7, , ,1.0,1590,
=BOX,908,9,904,-7, , ,1.0,1590,
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=BOX,357,14,356,
=BOX,457,14,456,
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3XT,75,90,100,110,120,
3YT,93.4,96.25,100,103.9,107.7,
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3YT,9.832,9.187,8.248,6.682,4.500,0,
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5IDEN,10,LOAD TORQUE
3ZT,9.5,20.2,39.3,57.5,81.0,
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 9.5,26.0,53.8,81.0,117.0,
 9.5,34.2,72.5,107.5,151.2,
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 9.5,60.5,140.0,214.0,302.8,
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3YT,0,50,80,100,120,
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5IDEN,10,AVAILABLE TORQUE
3ZT,0,-20.0,-28.5,-37.5,-55.2,
 99.5,77.5,66.2,55.2,33.8,
 206.8,181.2,168.2,155.8,130.3,
 314.2,285.3,270.8,256.5,227.5,
 399.3,368.2,352.5,336.8,305.0,
3XT,14.7,24,34,44,52,
3YT,0,50,75,100,150,
3AK,5,5,2,2,
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3ZT,14.70,13.25,13.02,13.002,13.000,
 15.30,13.8,13.5,13.4,13.3,
 15.90,14.5,13.9,13.7,13.6,
 16.70,15.2,14.5,14.1,14.0,
 17.50,16.1,15.1,14.6,14.4,
 18.30,16.9,15.7,15.1,14.5,
 19.30,17.8,16.5,15.9,15.4,
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 20.?,18.8,17.5,16.7,16.1,
 21.4,19.9,18.5,17.6,16.9,
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 43.2,42.6,41.8,40.4,38.6,
 45.2,44.7,43.9,42.6,40.9,
 47.2,46.8,46.0,44.7,43.0,
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3XT,0,200,400,600,800,
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3XT,10=,2000,2200,2400,2600,2800,
3XT,15=,3000,3200,3400,3600,3800,
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=BOX,261,11,224,262,
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=BOX,262,19,225, , , ,.5,
5IDEN,10,DIVERTER FUNCTION
3ZT,0,5.6,12.7,17.5,24.6,
 29.7,35.1,40.6,46.1,
 15.0,16.1,17.5,20.0,24.6,
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3XT,0,1200,
3YT,14.7,16.0,18.0,20,25,
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3AK,2,9,2,3,
=BOX,163,15,161,174,
=BOX,263,15,261,274,
=BOX,164,11,163,160,
=BOX,264,11,263,260,
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=BOX,265,9,261,-264,
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=BOX,266,10,265,1.0,0,
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3XT,0,20,30,80,
3YT,0,0,1,1,
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=BOX,267,14,260,
5IDEN,10,DIVERTER PRESSURE FUNCTION
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 14.7,14.7,
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 15.2,15.2,15.2,15.2,15.2,
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 237.2,118.6,59.3,39.6,30.5,
 24.1,20.9,19.0,18.0,17.7,
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 20.4,20.8,
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 22.3,23.2,24.2,25.1,25.8,
 26.4,26.9,
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3YT,15=,75,80,
3AK,7,17,3,3,
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=BOX,744,1, , ,0,
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5IDENT,10, ONE ENG FAILED   DIVERT 1.5 SFC
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=BOX,0,
5IDENT,10, TWO ENG FAILED   DIVERT 0 SFC
5IDEN,10, PLA MOTION ENG TWO
3XT,0,.999,1.0,5,
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=BOX,743,1, , ,1,
=BOX,744,1, , ,1,
=BOX,0,
5IDENT,10, TWO ENG FAILED   DIVERT 1.5 SFC
=BOX,743,1, , ,2.5,
=BOX,744,1, , ,2.5,
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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY *(Corporate author)* General Electric Company West Lynn, Massachusetts		2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE Investigation of Performance of Multiple Gas Generators With a Common Exhaust		
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Final Report		
5. AUTHOR(S) *(Last name, first name, initial)* Woodward, Roger M.		
6. REPORT DATE May 1966	7a. TOTAL NO. OF PAGES 168	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. DA 44-177-AMC-274(T) b. PROJECT NO. c. Task 1M121401A14415 d.	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Report 66-28 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* G.E. Report No. TM65SE-20	
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Aviation Materiel Laboratories Fort Eustis, Virginia	

A system wherein multiple engines exhaust into a common exhaust is analyzed on both a steady-state performance and transient response basis. A failure analysis of the system is also included.

Engine-to-engine variations have been considered together with the effects of externally induced mismatches.

It is concluded that maximum power is obtained by rating the engines on a T5 basis and trimming the exhaust area upon installation. It is shown that the greater the number of engines combined in a common exhaust, the lower the average performance compared to separately ducted engines; however, the averaging effect of the number of engines and the trim method recommended keep the minimum system performance above that which would be calculated from single-engine guarantee performance. A fundamental problem in the common engine system is that of acceleration delay or hangup resulting in deceleration during transient conditions. This problem can be eliminated in the two-engine system by using a high idle speed and can be prevented in the four-engine system by a combination of high idle speed and a simple gas generator coordination control.

If accessory power is to be extracted, this must be extracted equally from all engines.

Although the characteristics of the T64 engine and the hot gas cycle rotor were used, the results are believed to be applicable to a wide range of engine and aircraft configurations, including the lift fan and cruise fan. However, the simplicity of control of the two-engine system probably makes this system more attractive than the four-engine system.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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